Multivariate Statistical Models for Predicting Sediment Yields from Southern California Watersheds

By Joseph E. Gartner, Susan H. Cannon, Dennis R. Helsel, Mark Bandurraga

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Frontispiece: A debris flow in City Creek in San Bernardino blocked roads and buried infrastructure. Photo taken December, 2003, by the California Division of Forestry.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

Multivariate Statistical Models for Predicting Sediment Yields from Southern California Watersheds

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Abstract

Debris-retention basins in Southern California are frequently used to protect communities and infrastructure from the hazards of flooding and debris flow. Empirical models that predict sediment yields are used to determine the size of the basins. Such models have been developed using analyses of records of the amount of material removed from debris retention basins, associated rainfall amounts, measures of watershed characteristics, and wildfire extent and history. In this study we used multiple linear regression methods to develop two updated empirical models to predict sediment yields for watersheds located in Southern California. The models are based on both new and existing measures of volume of sediment removed from debris retention basins, measures of watershed morphology, and characterization of burn severity distributions for watersheds located in Ventura, Los Angeles, and San Bernardino Counties. The first model presented reflects conditions in watersheds located throughout the Transverse Ranges of Southern California and is based on volumes of sediment measured following single storm events with known rainfall conditions. The second model presented is specific to conditions in Ventura County watersheds and was developed using volumes of sediment measured following multiple storm events. To relate sediment volumes to triggering storm rainfall, a rainfall threshold was developed to identify storms likely to have caused sediment deposition.. A measured

volume of sediment deposited by numerous storms was parsed among the threshold-exceeding storms based on relative storm rainfall totals.

The predictive strength of the two models developed here, and of previously-published models, was evaluated using a test dataset consisting of 65 volumes of sediment yields measured in Southern California. The evaluation indicated that the model developed using information from single storm events in the Transverse Ranges best predicted sediment yields for watersheds in San Bernardino, Los Angeles, and Ventura Counties. This model predicts sediment yield as a function of the peak 1-hour rainfall, the watershed area burned by the most recent fire (at all severities), the time since the most recent fire, watershed area, average gradient, and relief ratio. The model that reflects conditions specific to Ventura County watersheds consistently under-predicted sediment yields and is not recommended for application. Some previously-published models performed reasonably well, while others either under-predicted sediment yields or had a larger range of errors in the predicted sediment yields.

Introduction

Southern California typifies both the wildland-urban interface and the fire-flood sequence. Cities, residential communities, highways, and other infrastructure are within close proximity to the steep mountain front formed by the Transverse Ranges. In some places, these mountains rise 2,500 m within 5 km. Low-pressure systems from the Pacific Ocean often cause storms that can last from a few days to a few weeks during the winter months (Arkell and Richards, 1986). These storms may lead to destructive floods and debris flows throughout the region, causing personal injury and damage to infrastructure and homes. The size and frequency of destructive debris flows and floods are exacerbated by annual wildfires that burn portions of these mountains. Steep watersheds, heavy winter rainstorms, and frequent wildfire combine to pose a continuous threat of floods and debris flows to communities throughout Southern California (figs. 1, 2).

Figure 1. Flooding and debris flow are common erosive responses to heavy rainfall in Southern California. (A) Flooding Ventura River erodes a road. (B) Woody debris was deposited by floods and debris flows in Twin Creek, San Bernardino, California.

Figure 2. Debris flow hazards are greatest immediately following fire and debris retention basins can be used to mitigate against these hazards. (A) Debris basin and spillway in Day Canyon in the San Gabriel Mountains of California. (B) Numerous homes were inundated by debris flows in Devore, California on December 25, 2003, following heavy rainfall on the area burned by the Grand Prix and Old fires.

Records of destructive floods and debris flows in Southern California date to the 1800s when the legendary 1862 floods affected nearly all of Orange County, Calif. (National Weather Service, 2007). Other notable storms that resulted in widespread flooding and debris flows in Southern California occurred during January and February 1934, February and March 1938, January and February 1969, and January 2005.

Debris flows following wildfires in Southern California have been recognized since the early 1900s (Eaton and others, 1935). Shortly following a wildfire in 1968 in the San Gabriel Mountains, debris flows overtopped debris basins and flowed into the city of Glendora (Scott, 1971). A fire-related debris flow in 1977 buried the town of Hidden Springs (Wells, 1987). Debris flows and floods following the 2003 Grand Prix and Old fires in San Bernardino County killed 16 people and were responsible for millions of dollars of damages (U.S. Army Corps of Engineers, 2005).

Wildfire facilitates erosion in many ways and can lead to debris flows. A water-repellent layer in the soil may form when the intense heat of a fire vaporizes hydrophobic materials in the undergrowth, litter, and duff (DeBano, 1981; Doerr and others, 2000). As temperatures cool, the vaporized hydrophobic materials condense a few centimeters below the surface and may limit infiltration of water into the soil (DeBano, 1981; Doerr and others, 2000). Fire also increases erosion potential by removing the canopy, litter, and duff, and by exposing bare ground to rainfall impact (Moody and Martin, 2001; Meyer, 2002; Cannon and Gartner, 2005). The introduction of ash into the soil, which can expand when wetted and seal pore spaces, also reduces the infiltration of water and increases runoff (Rompkins and others, 1990; Balfour and Woods, 2007).

Debris retention basins and networks of engineered channels are designed to mitigate hazards from floods and debris flows. Debris retention basins are commonly located at the mouth of a watershed and are designed to trap sediment and debris. A spillway and drain are designed to allow water to flow out of the retention basin and into a network of engineered channels. These channels safely pass the floodwaters through populated and developed alluvial fans and floodplains.

Previous Work To Predict Sediment Yields in Southern California

Records of the amount of material removed from debris retention basins following rainfall have provided data for developing empirical models to predict the amount of sediment deposited at a watershed outlet. The sizes of debris retention basins in Southern California were originally designed using a set of empirically-derived relations that predict sediment yield as a function of peak discharge, relief ratio, and a vegetation index (Rowe and others, 1949). Tatum (1965) used a similar empirical approach but incorporated correction factors for each of the variables in order to account for increased erosion rates observed following wildfire.

In 1969, a week-long storm resulted in widespread floods and debris flows throughout Southern California (Scott and Williams, 1978). Following this storm, additional data were available for sediment yields resulting from storms with long return intervals in Los Angeles and Ventura Counties. Data from the 1969 storm were used by Scott and Williams (1978) to generate two models that have been used to predict sediment yields for the Transverse Ranges in Los Angeles and Ventura Counties. One of the models uses the product of the 10-day antecedent rainfall and peak 24-hour storm rainfall intensity as one of the predictor variables. In the other model, rainfall is characterized by the mean annual precipitation at the site. In addition to basin and rainfall characteristics, these models included a fire factor to estimate how wildfire, and the elapsed time since a watershed burned, might affect sediment yield. Scott and Williams (1978) defined the fire factor as the percent of vegetative recovery multiplied by the percent of watershed burned within the previous 12 years, it ranges from 0 to 100. For example, if a watershed was 100 percent burned six months prior to being 88 percent recovered, the fire factor would be 88. The percentage of vegetative recovery was determined using air photos taken following the 1969 storm.

A set of models for predicting sediment yields were developed using data collected from the 1930s to 2000 by the U.S. Army Corps of Engineers (Gatwood and others, 2000). The models of the U.S. Army Corps of Engineers, Los Angeles District (USACE) predict sediment yield per unit discharge as a function of peak discharge, basin area, relief ratio, and a fire factor. The fire factor is determined using a set of curves that describe the increase in sediment yield observed following a fire (Gatwood and others, 2000). The sediment yield data for these models comes from cleanouts of debris basins located in Los Angeles County. In many cases, the volume of material removed from the debris retention basin was deposited during several storm events. The measured sediment yield was thus parsed among individual storms using the peak discharge measured at established stream gaging sites during storms known to have caused significant sediment yields. For basins larger than 3 mi^2, predicted sediment yields are divided by peak discharges at the associated gaging site.

Data from 80 debris retention basins located in the San Gabriel Mountains of Southern California between 1938 and 2002 were used by Pak and Lee (2008) to develop a model to predict sediment yields from multiple storm events. This study uses the relief ratio of a basin to determine the minimum rainfall total and intensity needed to produce a given sediment yield. The R^2 for this model is 0.76, and an adjustment factor is included for calibration of the model for local conditions if a sediment yield is known for individual storms.

Approach Used in this Study

In this study, we use multiple linear regression analyses to develop updated empirical models that can be used to predict potential sediment yields deposited from watersheds in Ventura, Los Angeles, and San Bernardino Counties. Measurements of sediment yields from individual floods and debris flows and the triggering storm rainfall conditions in Ventura and San Bernardino Counties that have not been used in previous studies supplement the existing data collected in Los Angeles County. The records of sediment yields in Ventura, Los Angeles, and San Bernardino Counties span seven decades (1938–2005). In addition, more specific information on burn severity and wildfire history has become available from the U.S. Geological Survey Monitoring Trends in Burn Severity Project (http://mtbs.cr.usgs.gov/viewer/viewer.htm). The project provides information on the distributions of low, moderate, and high burn severities within previously burned areas. A broad range of basin characteristics to be used as potential explanatory predictor variables can be accurately defined using digital elevation models (DEMs) and a geograpic information system (GIS). We use multiple regression analyses of these data to generate updated models to predict sediment yield for basins located in the Transverse Ranges of Southern California. The predictive strengths of the models developed here are compared to those of previously published models using an independent set of measured sediment yields retained from the compiled data. The parameters associated with each retained sediment yield were used with each model to predict sediment yields. These predicted volumes were then compared to the retained sediment yield volumes to evaluate each model's ability to accurately predict sediment yields.

Methods

Numerous explanatory variables that could potentially influence sediment yield were measured and used in the multiple regression analyses. These explanatory variables are divided into the following categories: watershed characteristics and morphology, fire history and burn severity, soil properties, and storm rainfall.

Watershed Characteristics and Morphology

Watershed characteristics that could potentially affect sediment yield include: watershed area (km^2), average watershed gradient (as an area weighted average of gradients present in each watershed), watershed area (km^2) with slopes greater than or equal to 30%, and watershed area (km^2) with slopes greater than or equal to 50%. Basins were delineated in ArcGIS (ESRI, 2003) using 10-m DEMs. Slopes greater than or equal to 30% and 50% were determined from slope grids and analyzed with the spatial analyst tools in ArcGIS to determine the area of each slope class within individual basins.

Measures of basin morphology thought to influence sediment yields include relief ratio, basin ruggedness, drainage density, and bifurcation ratio. Relief ratio is calculated by dividing the change in elevation between the basin mouth and the top of the longest channel extended to the drainage divide, by the length of that channel (Scott and Williams, 1978). Ruggedness is the maximum change in elevation within the basin divided by the square root of the basin area (Melton, 1965). Drainage density (m^{-1}) is calculated as the total length of streams in a basin divided by the basin area, and bifurcation ratio is the ratio of the number of streams of any order to the number of streams of the next highest order (Horton, 1945). For these variables, stream networks were defined based on a stream order pruning threshold of three, which corresponds to approximately 0.03 km^2 of contributing area for a first-order stream. Relief ratio and ruggedness were measured from DEMs using ArcGIS. Drainage densities and bifurcation ratios were determined by analyzing DEMs using River Tools (Rivix LLC, 2001).

Fire History and Burn Severity

The extent and severity of a wildfire in a watershed can be determined using the change in normalized burn ratio (dNBR). This technique uses satellite imagery taken before, and immediately following a wildfire to determine the extent of a wildfire, and to identify areas within the fire that burned at low, moderate, and high severities (Key and Benson, 2006). The dNBR reflects a measure of the biomass change in a watershed due to the fire and, thus, the effect fire might have on increasing erosion. Burn severity data were provided by the U.S. Geological Survey Monitoring Trends in Burn Severity (MTBS) Project (http://svinetfc6.fs.fed.us/mtbs/dataaccess.html) and are available for fires that burned between 1984 and the present. Historic records of burn perimeters exist for Los Angeles County from 1878 to present and for Ventura County from 1968 to present. Fires that predate the MTBS database are mapped as fire perimeters and were used to identify the area of a watershed burned. Figure 3 shows the available burn severity data for fires that burned watersheds used in this study.

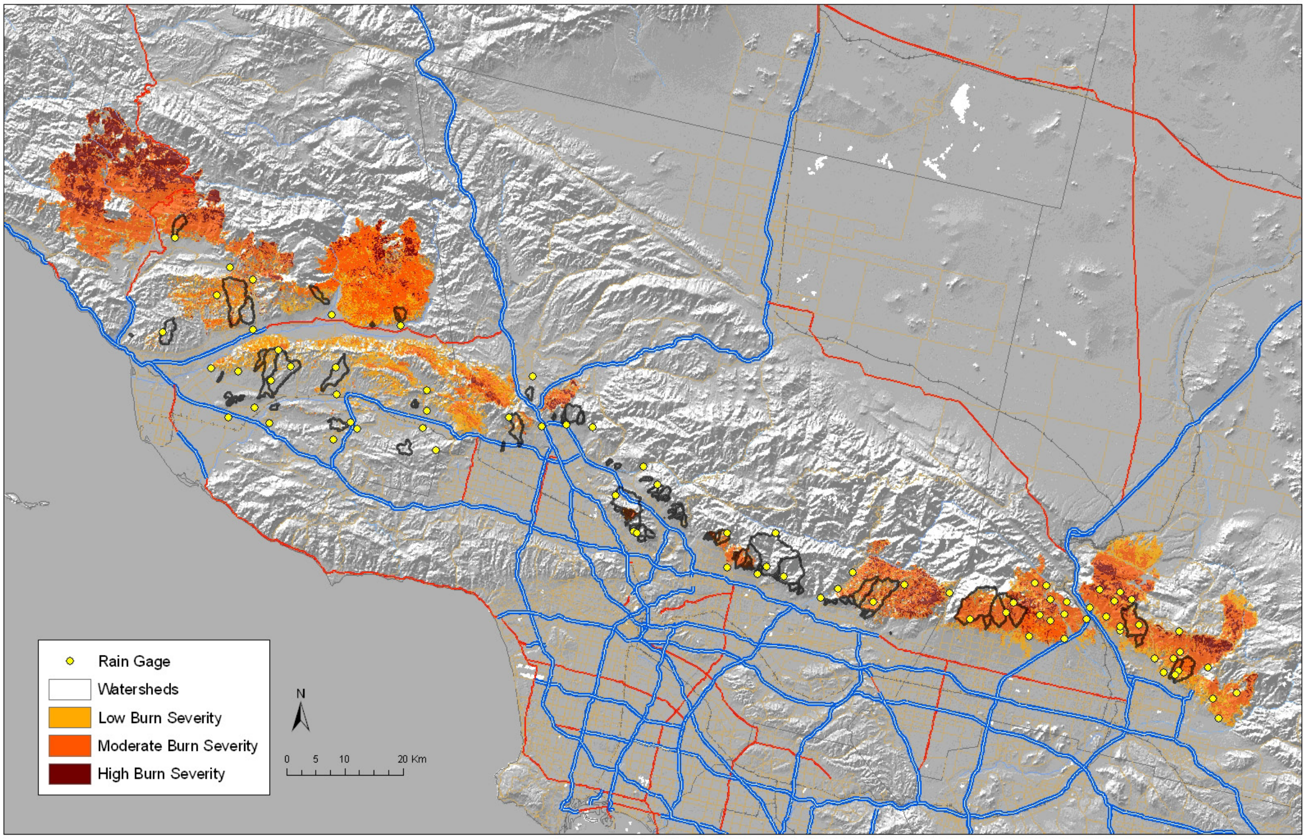

Figure 3. Map showing watersheds with debris retention basins used to develop new sediment yield predictive models for Southern California. Burn severity of fires that burned between 1984 and 2005, and locations of rain gages used in this study are also shown.

The erodability of a burned watershed decreases over time as plant life re-establishes on hillslopes and as litter and duff accumulates. After several years, the effect of a fire on erosion may be negligible. Rulli and Rosso (2005) found that the runoff ratio (the ratio of runoff to the amount of rainfall) measured from test plots in the San Gabriel Mountains of Southern California burned within one year were 20 to 60 times higher than the runoff ratios measured from test plots burned by a fire six years prior. They also found that suspended sediment yield in the more recently burned plots was more than two orders of magnitude higher than that produced from the plot burned six years prior. In addition, an evaluation of documented debris flows after fires indicated that the majority of debris flows occurred within two to three years of the wildfire (Cannon and Gartner, 2005). Rainfall amounts, watershed aspect, the severity of the burn, and type of flora may all affect how long it takes a watershed to recover from a fire.

To quantify the effects fire has on the erodibility of a watershed as a function of the time it takes for the watershed to return to its unburned state, we use an exponential decay function of the time (in years) since the most recent fire. We refer to this variable as the 'lingering effect', an empirical value that characterizes how the effect of a fire on erosion rates may decrease over time (figure 4). The following equation was used to calculate the lingering effect:

$$LE = e^{(-\lambda t)} \quad (1)$$

where

LE is the Lingering Effect

λ is the decay constant

and

t is the time since most recent fire (years)

Because of its exponential form, the lingering effect characterizes the effect of fire on sediment yields as being greatest immediately after the fire and then gradually tapering off over time. For example, if the decay constant was set to be 0.5, the lingering effect will be equal to 1.0 immediately following a fire, 0.6 one year following the fire, 0.4 two years following the fire, 0.08 five years following the fire, and 0.01 ten years following the fire.

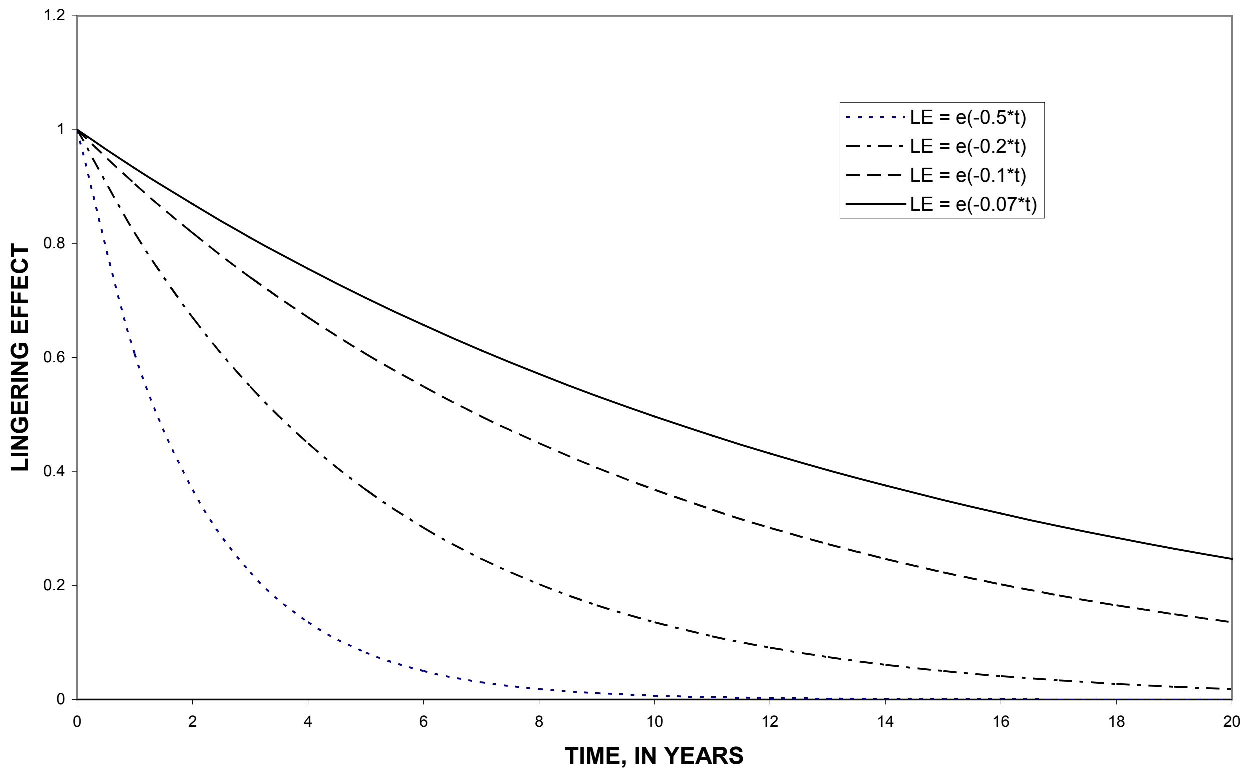

Figure 4. Plot showing variable estimates of decreasing erodability of a watershed (the lingering effect). Individual curves are based on different decay constants (λ=0.5, λ=0.2, λ=0.1, λ=0.07).

Soil Properties

A soil survey was used to identify the engineering properties of soils in each watershed. USSOILS is an ArcGIS coverage based on the state soil geographic (STATSGO) database, where the soil engineering properties for unmapped areas are extrapolated using inverse distance weighting (Schwarz and Alexander, 1995). Spatially weighted averages of the following soil engineering properties were determined for each watershed: available water content, percent clay, percent organic matter, k factor (erodibility), permeability, saturated hydraulic conductivity, and liquid limit. Although the USSOILS database is a broad-scale (1-km resolution) characterization of soil properties, it is the only coverage of soil information available for all of southern California. The soil survey geographic

(SSURGO) database (Natural Resources Conservation Service, 2008) provides more detailed soil surveys than those included in USSOILS. However, this database is incomplete for large parts of Los Angeles and San Bernardino Counties and thus was not used in this study.

Storm Rainfall

Rainfall conditions in the watersheds above debris retention basins used in this study were measured using networks of tipping bucket rain gages. The rain gages are part of networks installed and maintained by the Ventura County Watershed Protection District, the Los Angeles County Flood Control District, the San Bernardino Flood Control District, county-maintained ALERT (Automated Local Evaluation in Real Time) systems, and the U.S. Geological Survey. The rain gages we used for information were either located within, or within two kilometers of, watersheds with a sediment yield record. Figure 3 shows the locations of the rain gages used in this study and the outlines of the watersheds examined. The rain gages provide information for the total storm rainfall, storm duration, and peak intensities measured over different time intervals (10 min, 15 min, 30 min, 60 min, 2hr, 4hr, 6hr, 12hr, 24hr, and 72 hr). An individual storm is defined as having a minimum 25.4 mm of rainfall and periods of at least 20 hours of no rainfall preceding and following the storm. Based on these criteria, the number of storms that potentially contributed material to individual debris retention basins varied between 1 and 80.

Sediment Yields

Measures of sediment yields and storm rainfall were provided by the Ventura County Flood Watershed Protection District, the Los Angeles Flood Control District, and the San Bernardino Flood Control District. Sediment yield volumes provided by these counties reflect the amount of material removed from debris retention basins. These volumes were determined for each basin by counting the number of trucks filled during the cleanout of a debris retention basin or by comparing field or aerial photographic surveys of full and empty debris retention basins. Volumes of sediment yield may reflect material deposited by floods, debris flows, or both. The sediment yields recorded in debris-retention basins were deposited either by one storm or by a combination of several storms. In the case of the combination of several storms, many of these storms may not have been large enough to contribute significant sediment from runoff into the basin, or several storms may have deposited various amounts of sediment to the debris-retention basin.

For this study, we used the available data to develop a database consisting of measured volumes of sediment yield that could be confidently attributed to a single storm event (termed the "single event volume" database, appendix 1). Debris-retention basins in San Bernardino County were largely empty prior to a large rainstorm and debris flow and flooding event on December 25, 2003. The amount of sediment from these basins was recorded and known to have been a result of the December 25, 2003, storm. Similarly, individual volumes of sediment in some Los Angeles County debris-retention basins were known to have been deposited by storms that occurred in January, February, and October of 2005. For other basins in Los Angeles County, we used previously published volumes of sediment yield for which stream discharge data was used to parse those volumes among storms known to have deposited significant volumes of sediment yield in debris-retention basins (Gatwood and others, 2000). Peak discharge data were not available for the Ventura County watersheds examined in the study, and storms that might have deposited sediment in the Ventura County debris-retention basins were identified using records of formal Federal Emergency Management Agency (FEMA) disaster declarations. If there was only one disaster declaration during the period between debris basin cleanouts, and if one storm during the month of the disaster declaration was significantly larger than any of the other storms, then that storm was used to represent the rainfall conditions that resulted in the measured sediment yield. Our intention was to develop an accurate dataset rather than try to use all of the available data. For example, if multiple disasters were declared within one month, then the sediment yield data from that period were not used in the analysis.

A second database was compiled consisting of volumes of sediment that could not be confidently associated with a single storm. This database consisted of sediment yields from Ventura County watersheds and is termed the "divided volume" database (appendix I). A rainfall threshold was developed to identify significant storms, and the volume of sediment deposited in a debris-retention basin by multiple storms was divided among the significant storms. The rainfall intensity-duration threshold was identified by examining the records of rainstorms during periods where no sediment accumulated in individual debris retention basins. Peak intensities of each of these storms measured over different time intervals were used to identify the threshold rainfall conditions below which sediment delivery to a basin would not be expected (figure 5). The threshold line was determined using a regression of the five highest rainfall totals measured for each duration (55 values total).

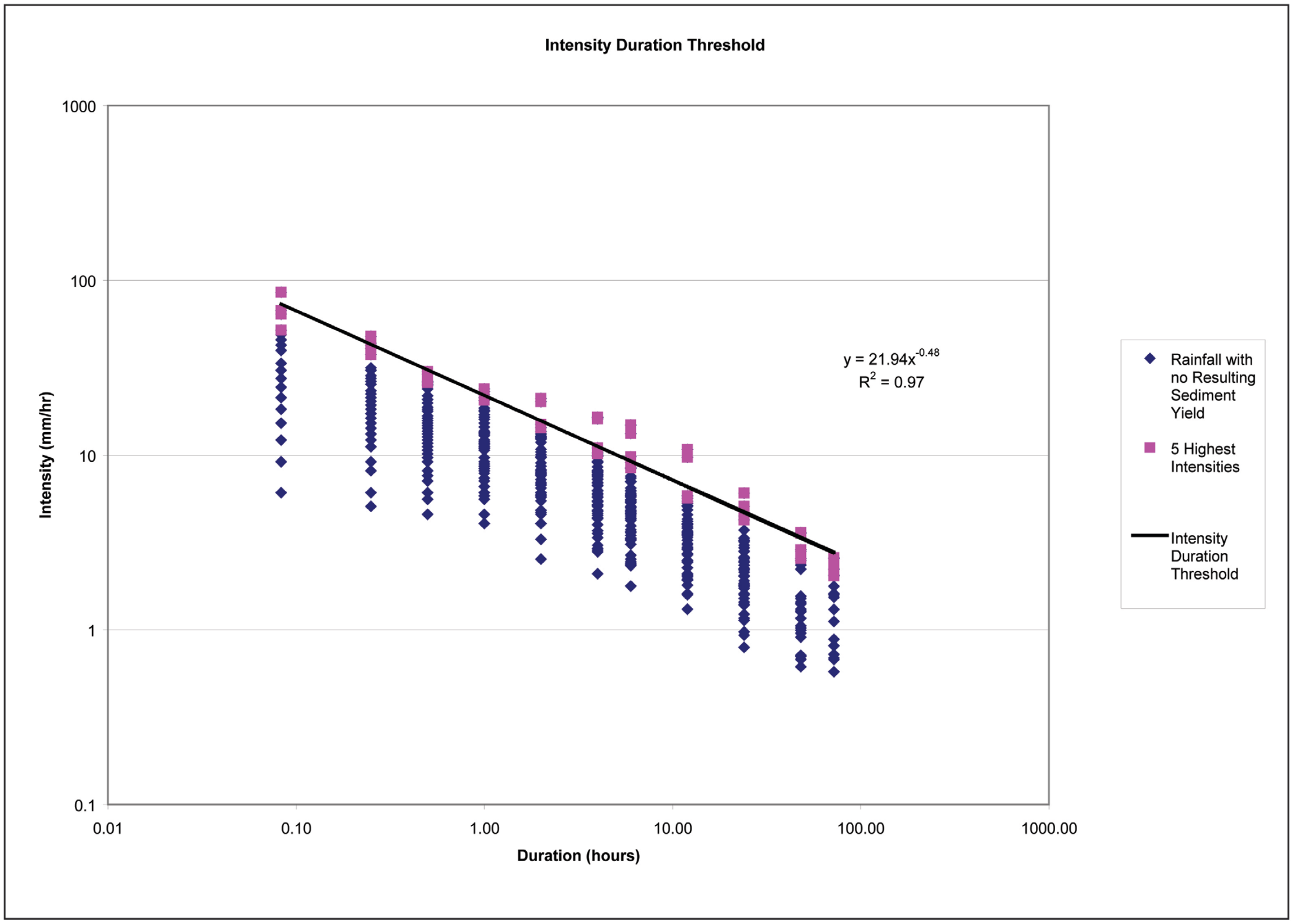

Figure 5. A rainfall intensity-duration threshold indicating storm rainfall conditions below which no sediment production is expected. All of the points represent storm conditions where no sediment was delivered to a debris retention basin. The threshold line is a regression of the five highest intensities for each 5-, 15-, and 30-min duration, and for each 1-, 2-, 4-, 6-, 12-, 24-, 48-, and 72-hour duration (55 values total).

Storms that recorded no peak intensities greater than the threshold were assumed to have delivered no sediment to the debris retention basins. Sediment yields measured in debris-retention basins were thus divided among threshold-exceeding storms. Total storm rainfall has been shown to be related to the volume of material produced from burned watersheds (Gartner and others, 2008), and so the amount of sediment attributed to each individual storm was calculated as the product of the total measured sediment yield and the threshold-exceeding storm rainfall total, divided by the total storm rainfall over the period of sediment accumulation in the debris retention basin. Because of the uncertainties associated with parsing sediment yield totals by storm rainfall, we have less confidence in this database than we do in the single event volume database.

Multiple Regression Analyses

We used multiple linear regression analyses to develop models that can be used to predict sediment yields for individual watersheds. Models were developed from both the single event volume and divided volume databases. We used a method of building multiple regression models and evaluating them using a variety of tests recommended by Helsel and Hirsch (2002) that identifies the best multiple regression model for a given dataset.

First, the distribution of the independent and dependent variables were analyzed for normality using partial plots. Skewed data were logarithmically transformed (base 10), or if the variable contained zero values, the square root of the variable was used to avoid undefined data. A best subsets regression uses all possible combinations of independent variables against the dependent variable and determines the best models based on Mallows Cp, and adjusted R^2. The independent variables used in one of the better models determined by the best subsets regression is then used in a linear multiple regression.

The linear multiple regression model is further evaluated based on several factors. Partial plots are first checked to see if any of the variables need to be transformed to a normal distribution. These plots demonstrate how each independent variable behaves in the model; they should show linear trends. If a partial plot had an exponential shape, the variable was transformed. A variable that had a range of greater than one order of magnitude was also transformed (Helsel and Hirsch, 2002). After the necessary variables were transformed, a new linear multiple regression model was generated. Multicolinearity was checked using a Variance Inflation Factor (VIF) which, if much larger than 10, indicates that two or more independent variables are collinear (Helsel and Hirsch, 2002). Confidence in the coefficients of the variables, represented by the p-value of each coefficient, was at least 95 percent. Residual plots were checked for constant variance and an absence of trends in the residuals.

The Adjusted R^2 and the Predicted Residual Sum of Squares (PRESS) statistics were used to evaluate multiple models generated from the same datasets. The Adjusted R^2 is an R^2 value that has been adjusted for the number of independent variables and indicates how well the dependent variable is explained by a set of independent variables. The PRESS statistic evaluates the predictive ability of the model, and lower PRESS statistics indicate better models (Helsel and Hirsch, 2002). The PRESS statistic is determined by first iteratively developing models using all but one of the observations. Each iteration leaves out a different observation. The model is used to predict a value for the observation left out, and the difference between the predicted and measured value (the predicted residual) is calculated. The sum of the squared predicted residuals is the PRESS statistic (Helsel and Hirsch, 2002).

If a variable had either a low p-value or a high VIF, it was removed from the model and the model was re-evaluated. The residual standard error (S) represents the standard distance data values fall from the regression line and a lower S value indicates a better model. The residual standard error (S) also forms the basis for a bias correction for the model, which is calculated as one half of S squared (Helsel and Hirsch, 2002) . When the log of the sediment yield is calculated, it is a median value. Adding the bias correction to the predicted median volume of sediment yield transforms it to a mean value.

Model Verification

A validation dataset (Appendix I) was used to evaluate how well each model predicted sediment yields in terms of accuracy, consistency, and ease of application. Forty-eight randomly selected, measured sediment yields were removed from the compiled dataset to be used as a validation dataset. These data were not used in the development of the updated models. However, some of these data had been used to develop existing models (Scott and Williams, 1978; Gatwood and others, 2000; Pak and Lee, 2008). To supplement these data, 17 sediment yields known to have been deposited by a single storm were used to test the existing models with independent data. Sediment yields were predicted using each model and compared to the measured sediment yields from the test database. A comparison of the predicted sediment yields to the measured sediment yields was used to evaluate each model.

Results

Several models were developed using multiple regression analyses. The two models presented here represent the best models developed from each of the two datasets. Model 1 is derived from the single event volume database for watersheds located throughout Ventura, Los Angeles, and San Bernardino Counties. Model 2 is derived from the divided volume database that includes watersheds only in Ventura County.

Model 1 predicts sediment yield based on the following equation;

$$log(V) = 2.2 + 0.7 \times log(R) + 0.1 \times \sqrt{B} + 0.3 \times LE + 0.5 \times log(A) + 0.02 \times S - 2.1 \times RR + 0.5^2 \times 0.5, \qquad (2)$$

where

V is the volume of sediment yield (m^3)

R is the peak 1-hour rainfall (mm)

B is the area of watershed burned by most recent fire (km^2)

LE is the lingering effect (λ=0.5)

A is the watershed area (km^2)

S is the average watershed gradient (%)

RR is the relief ratio (m/m).

Adjusted R^2 = 0.49

PRESS = 106.74

and

S = 0.53.

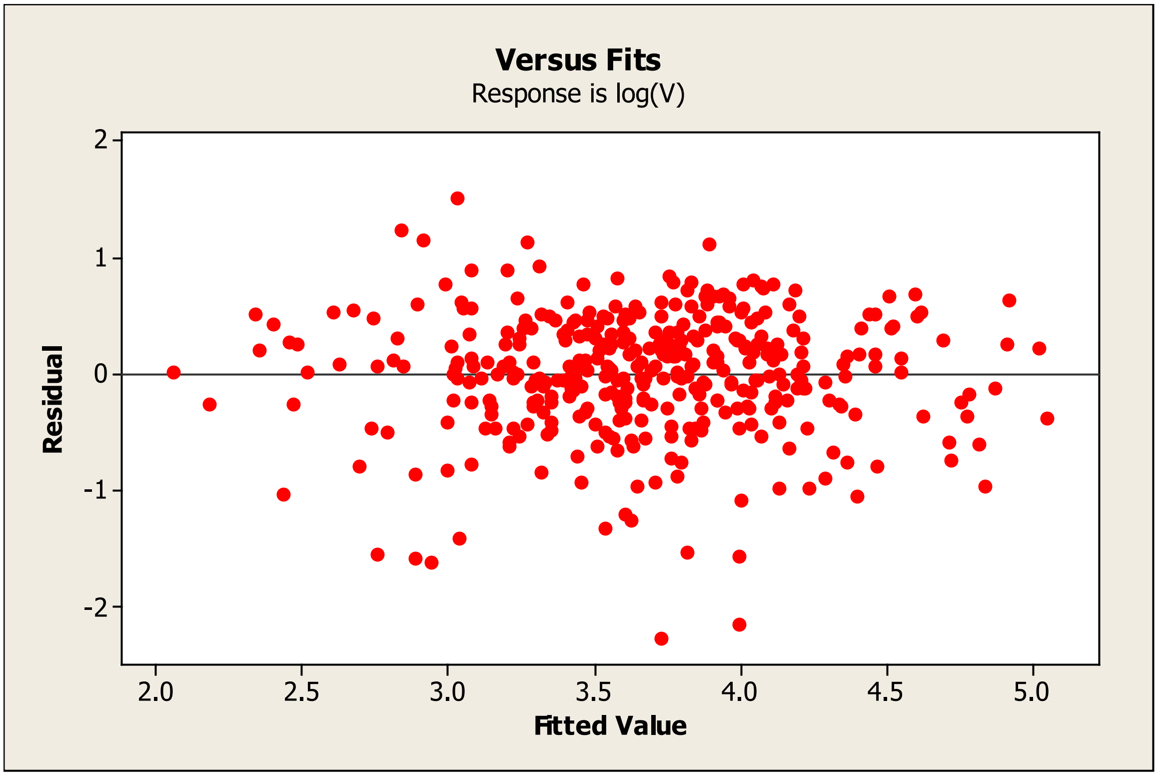

Figure 6. Residual plot for model 1. Log(V):[log(V) indicates the log of the sediment yield in m^3]

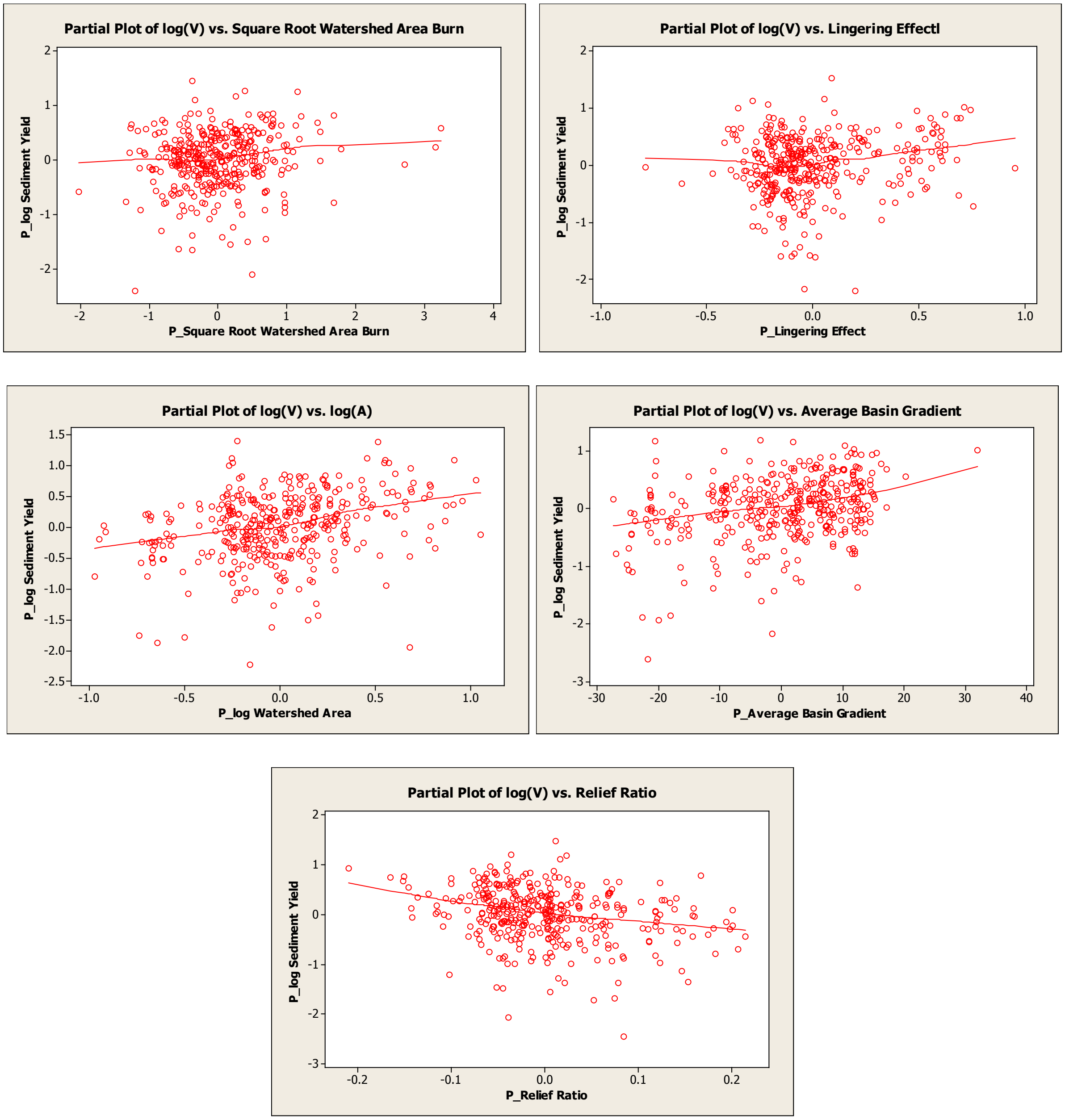

Figure 7. Partial plots for predictor variables used in Model 1. Log(V): [log(V) indicates the log of the sediment yield in m^3]. Log(A): [log(A) indicates the log of the watershed area in km^2]

Model 2 predicts sediment yield based on the following equation;

$$log(V) = 0.9 + 0.6\times log(A) + 0.1\times\sqrt{B} + 0.3\times LE + 0.9\times log(R) + 0.16\times D - 0.02\times C + 0.6^2\times 0.5, \quad (3)$$

where

D is the drainage density

C clay content

Adjusted $R^2 = 43.7$

PRESS = 290.93

and

S = 0.60.

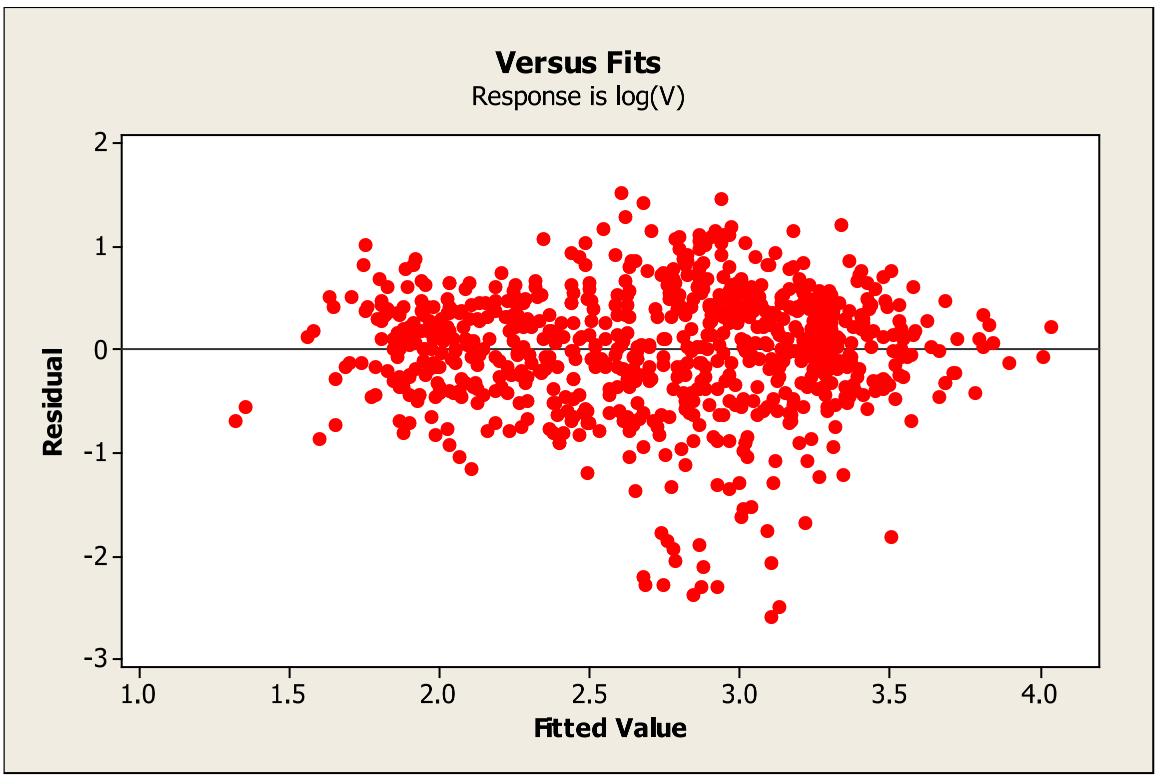

Figure 8. Residual plot for model 2. Log(V): [log(V) indicates the log of the sediment yield in m^3]

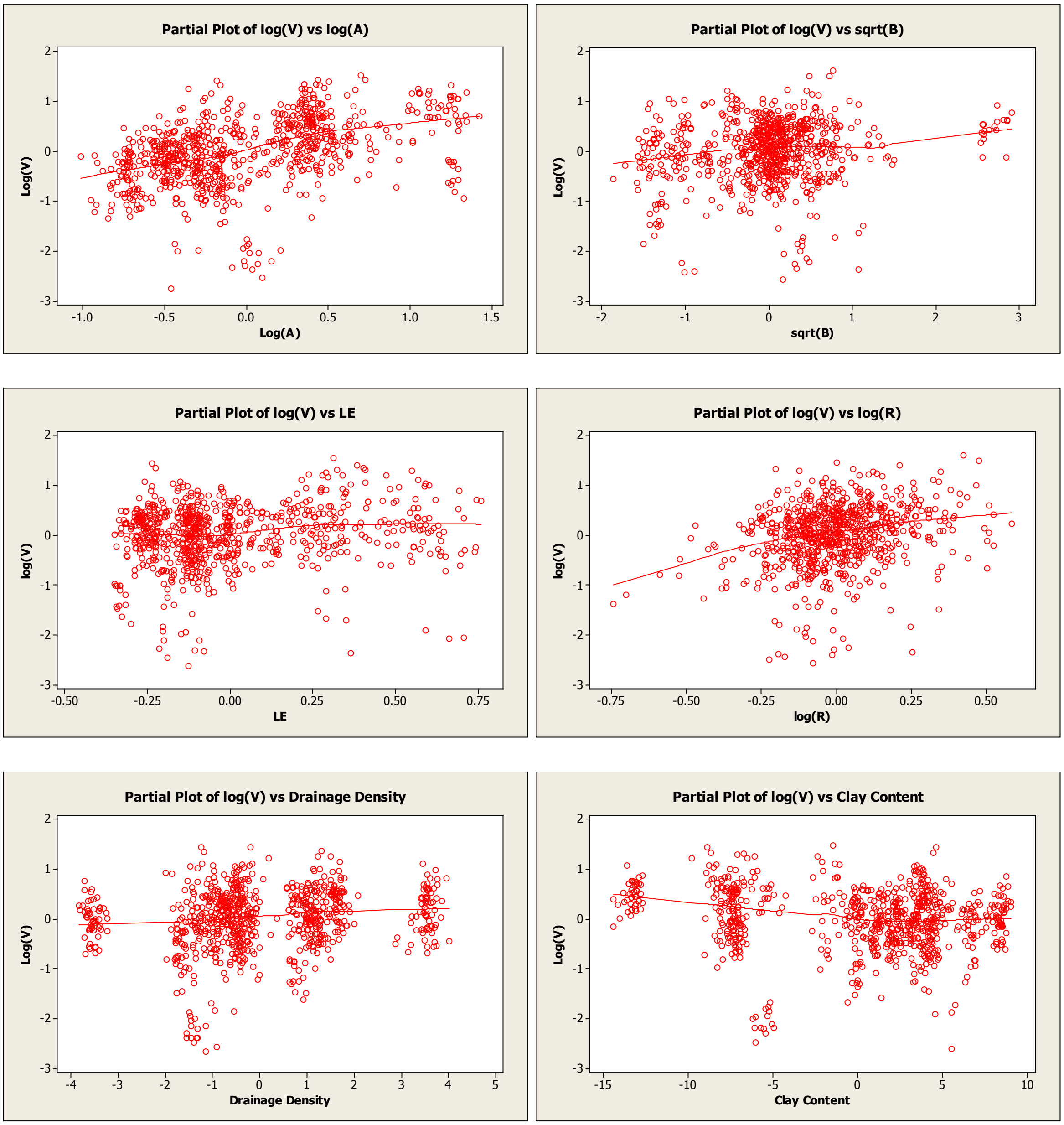

Figure 9. Partial plots for predictor variables used in model 2. Log(V): [log(V) indicates the log of the sediment yield in m^3]. Log(A): [log(A) indicates the log of the watershed area in km^2]. Sqrt(B): [sqrt(B) indicates the square root of the watershed area burned by most recent fire in km^2]. Log(R): [log(R) indicates the log of the peak 1-hour rainfall total in mm].

These models have the highest adjusted R^2, the lowest PRESS statistics, and the lowest residual standard error (S) of all the models developed from each of the datasets. Confidence in the variables used in each model is at least 95 percent (appendix 2). The residuals for the models are normally distributed and the variance is constant (figs. 6, 8). Partial plots for each of the variables show linear trends between the independent and dependent variables (figs. 7, 9). Variables that required logarithmic transformations included the sediment yield, the peak one-hour rainfall total, and the basin area. The square root of the area burned by the most recent fire was used because some watersheds had never burned and a zero value could not be logarithmically transformed.

The exponential decay function, used to model the lingering effect of fire on erosion, was most effective with a decay constant of 0.5. Of the decay constants evaluated (0.5, 0.2, 0.1, and 0.07), the lingering effect with a decay constant of 0.5 was the only variable significant in the multiple regression analysis. In addition, field and aerial photographic studies of 210 debris flow producing basins located throughout the Western United States indicate that most debris flows and sediment-laden floods occur within two to three years following a fire (Cannon and Gartner, 2005). This lingering effect variable corresponds with the observation that the largest fire-related debris flows tend to occur within two years following a fire.

A comparison of sediment yields predicted by model 1 (derived from the single event volume database) using the test dataset indicates that this model best predicts sediment yields (table 1 and fig. 10). Of all the models tested, this model predicted the most volumes to within an order of magnitude of the measured volumes (table 1). The model best predicts volumes between about 1,000 m^3 and 10,000 m^3, where most of the points are clustered around the 1:1 line. Although the model mostly over-predicts sediment yields, it rarely does so by more than an order of magnitude. A comparison of sediment yields predicted by model 2 (derived from the divided volume database) using the test dataset indicates that this model is inadequate because it predominantly under predicts sediment yield (fig. 11). The Scott and Williams (1978) model that includes antecedent and total storm rainfall as a predictor variable also predominantly under-predicted sediment yields of the test dataset (fig. 12). The Scott and Williams (1978) model that includes mean annual precipitation predicts fewer of the measured volumes to within an order of magnitude (fig. 13). The USACE (Gatwood and others, 2000), and the Pak and Lee, (2008) model both predict a reasonable amount of sediment yields to within one order of magnitude; however, the predictions are not as clustered around the 1:1 line and more volumes are under-predicted (Figs. 14, 15).

Table 1

Model	**% Over-predicted**	**% Under-predicted**	**% Over-predicted by more than one order of magnitude**	**% Under-predicted by more than one order of magnitude**	**% Predicted within an order of magnitude**
Model 1	77	23	15	0	85
Model 2	8	92	0	40	60
Scott and Williams (1978)-1	47	53	16	7	73
Scott and Williams (1978)-2	10	90	0	48	52
Gatwood and others (2000)	40	60	20	3	77
Pak and Lee (2008)	50	50	22	3	75

1. Table showing effectiveness of each model for predicting sediment yields not used to develop the model. Measures include the percent of values over- and under-predicted, percent of values over- and under-predicted by more than one order of magnitude, and percent predicted to within one order of magnitude.

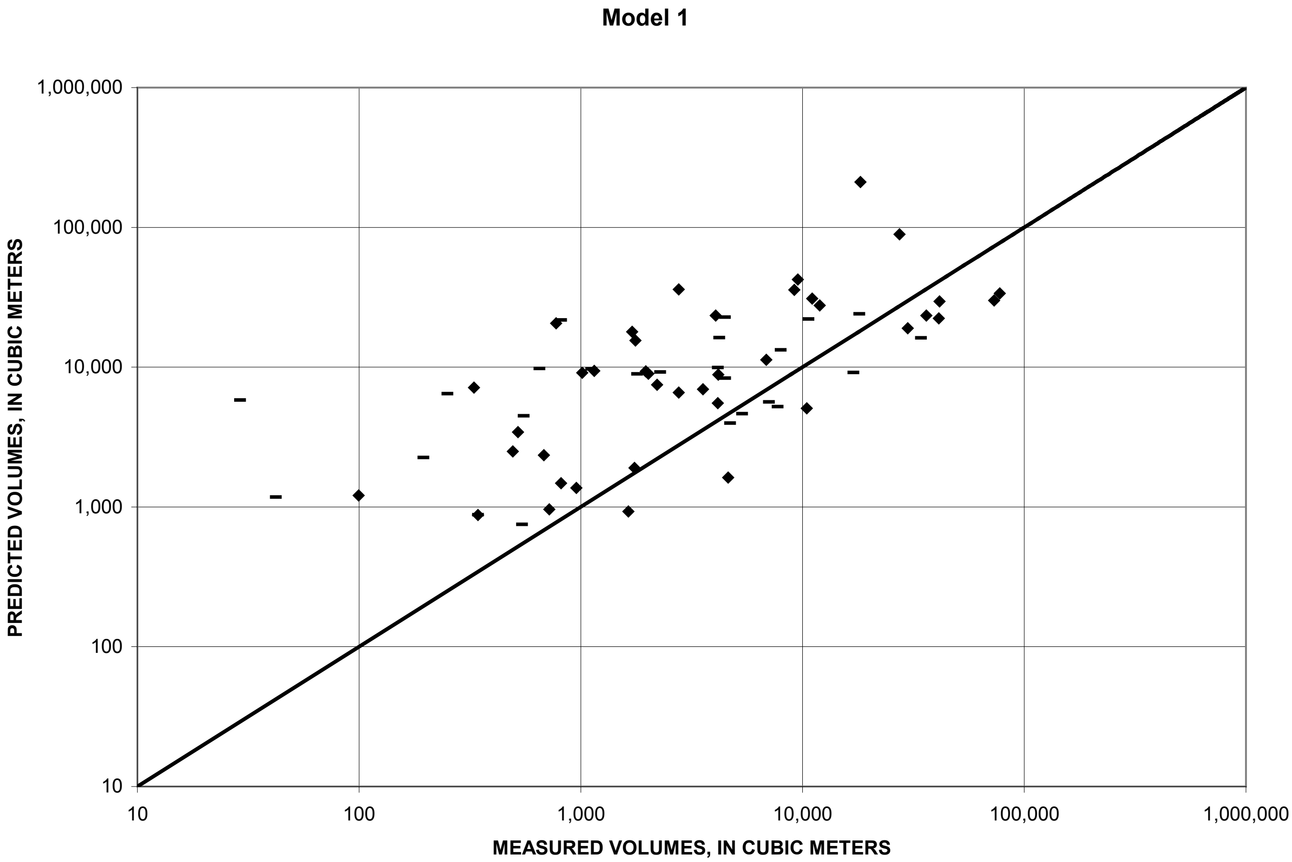

Figure 10. Sediment yields predicted by model 1 with the volumes not used to derive this model in the test dataset are represented as filled diamonds. Model 1 was developed using the single event volume database. Volumes used to develop this model are shown by dashes. Exact agreement of the predicted and measured volumes is shown by the 1:1 line.

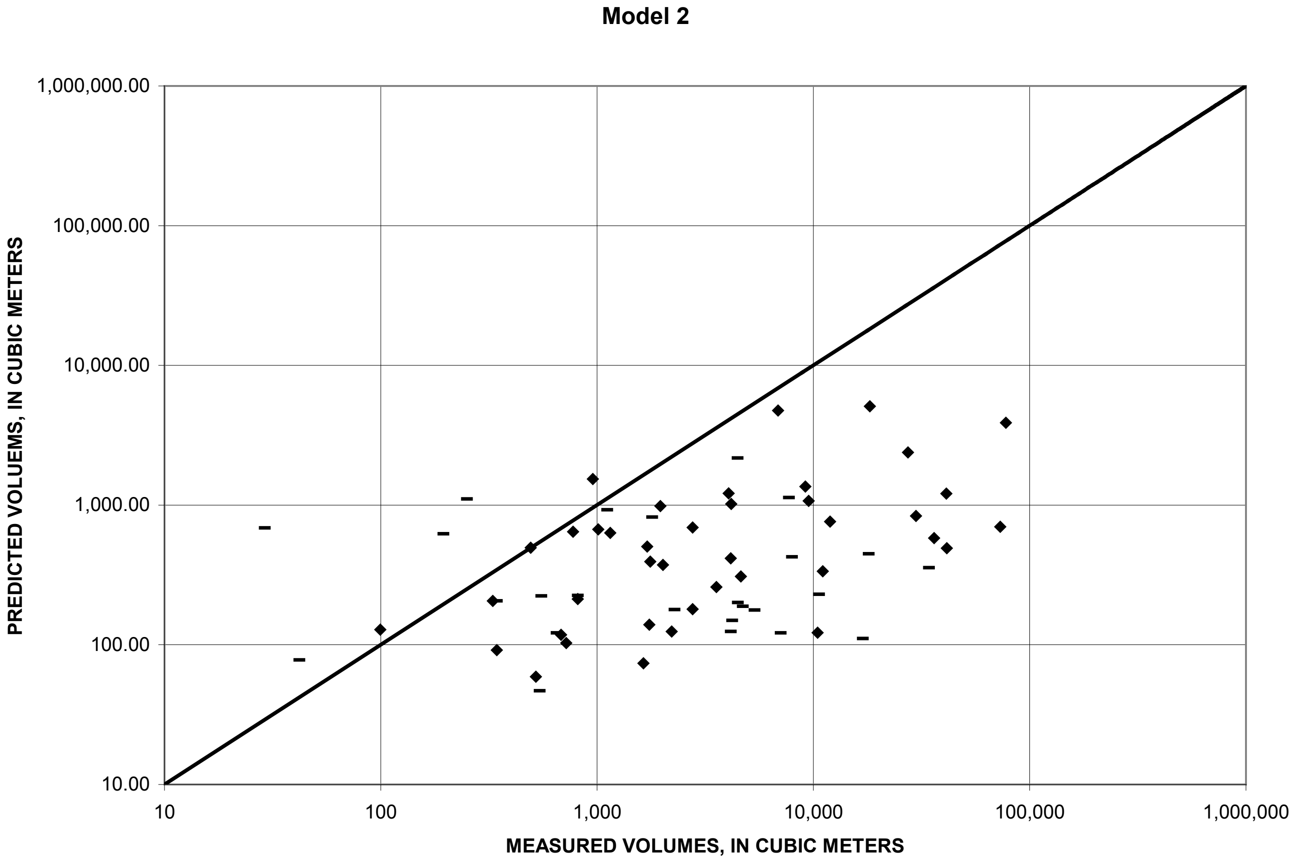

Figure 11. Sediment yields predicted by model 2 with the volumes not used to derive this model in the test dataset are represented as filled diamonds. Volumes used to derive the model are represented as dashes. Model 2 was developed using the divided volume database. Exact agreement of the predicted and measured volumes is shown by the 1:1 line.

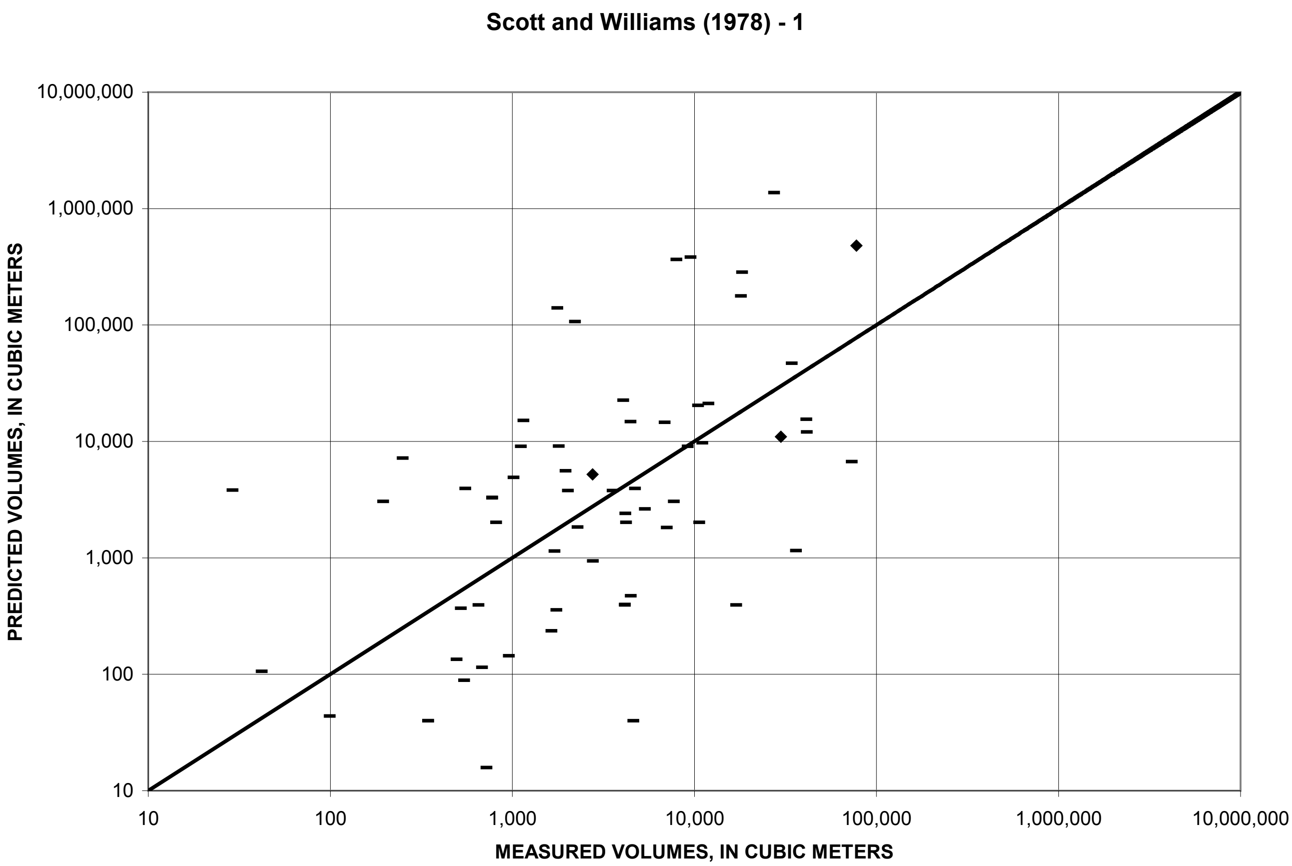

Figure 12. Sediment yields predicted by the Scott and Williams (1978) model with the volumes not used to derive this model in the test dataset are represented as filled diamonds. Volumes used to derive the model are represented as dashes. This model uses mean annual precipitation as a predictor variable. Exact agreement of the predicted and measured volumes is shown by the 1:1 line.

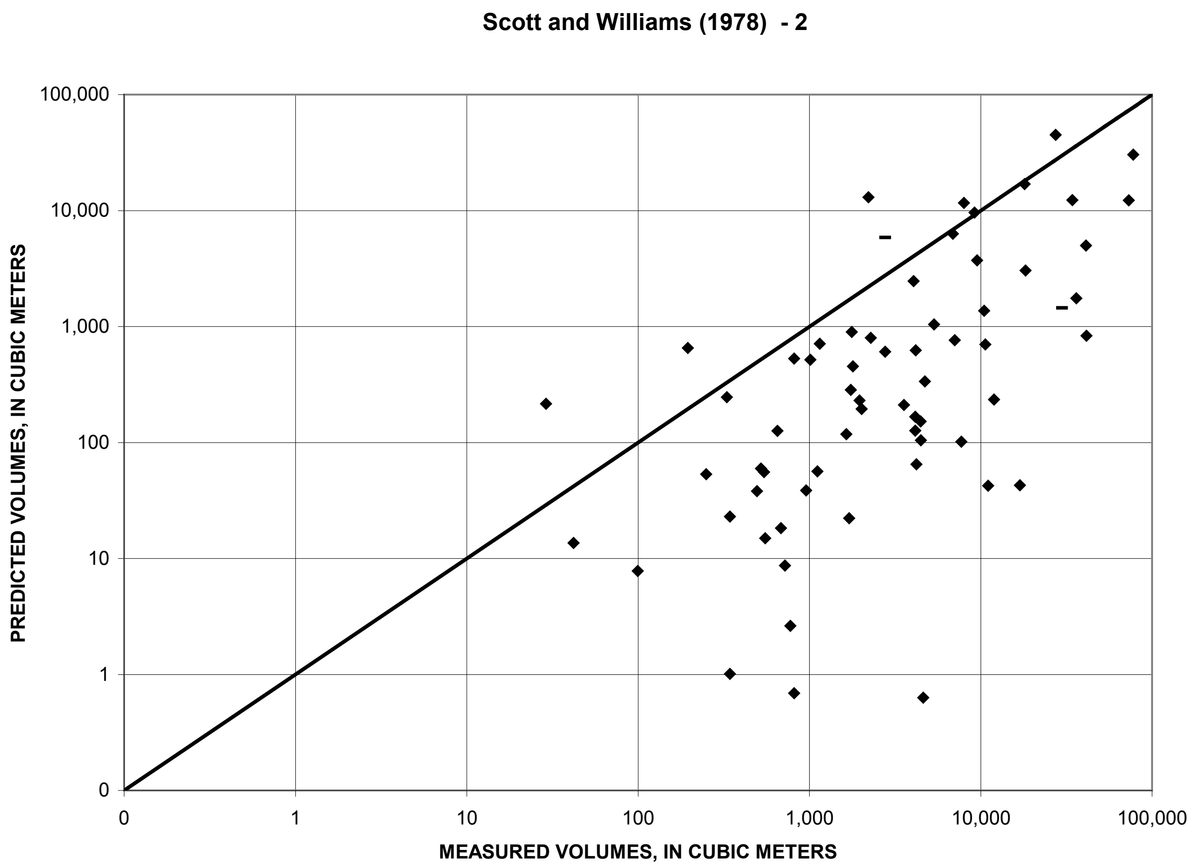

Figure 13. Sediment yields predicted by the Scott and Williams (1978) model with the volumes not used to derive this model in the test dataset are represented as filled diamonds. Volumes that were used to derive the model are represented as dashes. This model uses the product of the 10-day antecedent rainfall and the peak one-hour rainfall as a predictor variable. Exact agreement of the predicted and measured volumes is shown by the 1:1 line.

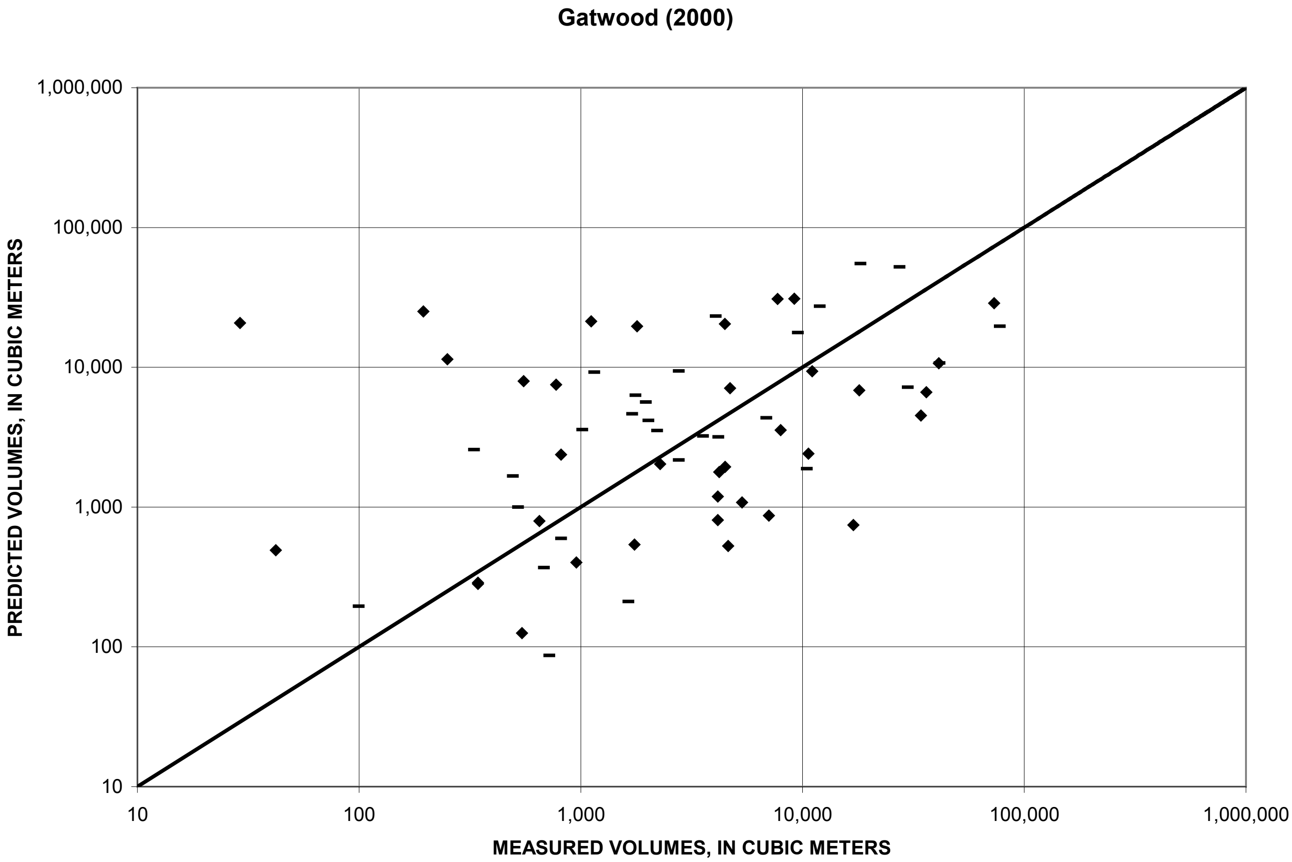

Figure 14. Sediment yields predicted by the U.S. Army Corps of Engineers, Los Angeles District model (Gatwood and others, 2000) with the volumes not used to derive this model in the test dataset are represented as filled diamonds. Volumes used to derive the model are shown as dashes. Exact agreement of the predicted and measured volumes is shown by the 1:1 line.

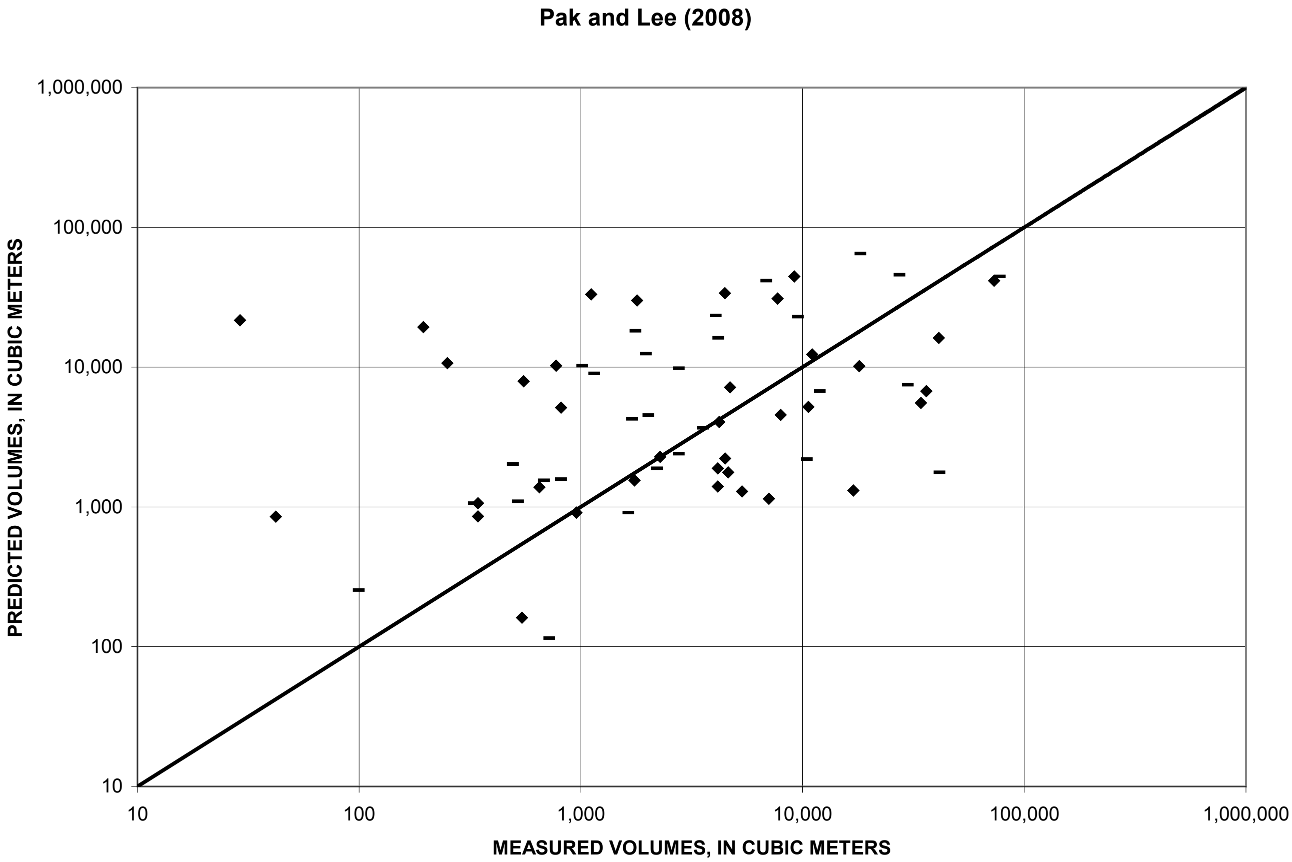

Figure 15. Sediment yields predicted by the Pak and Lee (2008) model with the volumes not used to derive this model in the test dataset are represented as filled diamonds. Volumes used to derive this model are shown as dashes. Exact agreement of the predicted and measured volumes is shown by the 1:1 line.

Discussion

In this study we use the most current information available on sediment yields, triggering storm rainfall conditions, basin morphology, fire history, burn severity, and soils to develop new models to predict potential sediment yields for watersheds in Southern California. These new models use information on sediment yields and storm rainfall collected between 1938 and 2005 in Ventura, Los Angeles, and San Bernardino Counties. The new models were evaluated using adjusted R^2, PRESS, residual plots, partial plots, and their ability to predict sediment yields using a test dataset not used to derive the models.

Out of all of the models analyzed in this study, model 1 demonstrates the strongest predictive capability. This model predicts the highest percentage of volumes of sediment yields not used to develop the model to within an order of magnitude. Very few volumes are under-predicted and many of the volumes are slightly over-predicted, but rarely by more than an order of magnitude. This model consists of variables that are readily defined and satisfies the statistical requirements of the procedure used here. In addition, each of the variables used by this model has a physical relation with sediment yield. The lingering effect of fire, combined with the watershed area burned by the most recent fire, enables the model to characterize how the history and extent of fire in a watershed affects sediment yield. Relief ratio was negatively correlated to volume. Smaller basins correlate to high relief ratios and therefore to smaller sediment yields. The average watershed gradient is included in the model and reflects how steeper gradients promote soil detachment and provide less resistance to continued movement. The peak one-hour rainfall total describes how intense rainfall is required for sediment transport in ephemeral streams that drain steep, mountainous watersheds.

The models presented here are empirical and therefore do not necessarily account for all of the factors that may affect watershed-scale sediment yields. For example, the extent and severity of wildfire increases the amount of sediment that may be deposited at a watershed outlet (Cannon and Gartner, 2005); however, none of the variables describing burn severity were found to be significant explanatory variables for sediment yield. Techniques used to map burn severity have improved and remote sensing enables consistent burn-severity maps. Burn severity mapping using the dNBR was originally developed for conifer forests of the Western United States and divisions between low, moderate, and high severities may not be as accurate when used for chaparral dominated landscapes. This is a potential reason why burn severity (dNBR) did not appear as a significant variable in our model. In addition, the adaptation of chaparral to frequent wildfire is exhibited by its ability to quickly sprout new growth following a fire.

Precipitation accumulations in the years following a fire affect how quickly vegetation returns to the burned area and the influence of the fire on sediment yield. For example, debris flows occurred immediately following the 2005 Harvard fire in Burbank Calif., and again three years later. The initial years following the fire were during record drought conditions which delayed the reestablishment of plant life on the hillslopes, leading to an extended period of elevated debris-flow hazards in the area. Antecedent rainfall may also influence how much runoff will occur following a rainstorm. However, variables describing these rainfall conditions were oftentimes unavailable and could not be included in the models. Although these variables were not included in the models, this information could still be collected and qualitatively taken into consideration when applying the models. For example, if one were using the model to predict sediment yield from a watershed burned four years prior, and a few of those years were very dry, then the analyst may err on the more positive side of the prediction interval.

A comparison of the models presented here with those previously developed using an independent dataset indicates that model 1, derived using the single event volume database, best predicts sediment yields. Measures of sediment yields deposited by individual storms generate the strongest predictive models. Future studies on how to predict sediment yields will benefit from better documentation of which storms cause heavy runoff and large sediment yields in debris retention basins.

The Scott and Williams (1978) model that includes mean annual precipitation as a predictive variable is somewhat effective in estimating sediment yield; however, the predictions are not specific to an individual storm. Still, the model more or less evenly under- and over-predicts along the entire range of potential sediment yields and thus may be a reasonable indicator of the amount of material that may be deposited by a typical storm that may affect the area. The Scott and Williams (1978) models are based on data from the 1969 storm only and contain some variables that are difficult to derive. For example, the fire factor is based on the percent recovery of a watershed as determined from post-sedimentation event air photos. If such air photos are unavailable, then the fire factor can only be inferred based on time and the original extent of the fire.

The models of the USACE (Gatwood and others, 2000) also provide reasonable results. However, for basins larger than 3 mi^2, peak discharge is used as a predictor variable for sediment yield per unit discharge ($m^3/m^3/s$). If the peak discharge in a watershed that may result for a given storm was unknown (that is, the watershed is ungaged), then the model cannot be used to predict sediment yield. In addition, since peak discharge was used both to parse sediment yields and as a predictor variable in the model, it is not an independent predictor variable for sediment yield.

The Pak and Lee (2008) model produces reasonable results only for a range of volumes between 1,000 and 10,000 m^3. The model evenly under- and over-predicts sediment yield and it should be taken into consideration that under-predicted sediment yields are likely when using this model. Additionally, this model is based on only data from the San Gabriel Mountains in Southern California and may not be applicable to other areas within the Transverse Ranges of California.

Model 1 has a variety of applications. It can be used as one piece of information to determine the proper size for debris-retention basins in Southern California, to estimate how much sediment might have accumulated in a debris-retention basin or fanhead in response to a specific storm, and(or) to assess debris flow and flooding hazards immediately following wildfire. The model reflects a variety of conditions, observed across a large portion of the Transverse Ranges in Southern California, over a 70-year period. It is validated using an independent dataset, and statistically describes the relations between sediment yield and a variety of predictor variables.

Summary and Conclusions

Measurements of sediment yields accumulated in debris-retention basins in Ventura, Los Angeles, and San Bernardino Counties were used in combination with a set of variables describing the watershed source areas to develop two empirical models that predict potential sediment yields from rainstorms. Sediment yields measured in debris-retention basins were deposited by either one or several storms. Formal disaster declarations were used to identify individual storms that produced sediment yields. This method was used to supplement existing data for single event sediment yields in Los Angeles and San Bernardino Counties with information from Ventura County. Model 1 was developed from this dataset. Model 2 reflects sediment yields for watersheds located in Ventura County where volumes were divided among threshold-exceeding storms based on total storm rainfall. The rainfall threshold is based on storms that produced no sediment yields. Both models were tested using an independently measured dataset. Model 1 produced reliable results, whereas model 2 was found to under-predict sediment yield for the same dataset. Previously developed models were also tested using the independently measured dataset and were outperformed by model 1.

Our results suggest that dividing measured sediment yields among several storms and using these data to develop models that predict sediment yield will result in models that consistently under-predict sediment yield. Sediment yields measured immediately following a storm and known to be related to conditions within that storm are preferable for developing empirical models to predict sediment yield. Future refinement of models to predict sediment yield could benefit from more single event volume data.

We recommend model 1 for predicting sediment yield volumes in Southern California. This model is statistically robust, contains predictor variables with a physical relationship to sediment yields, and was validated using an independent dataset. In addition, the variables needed to implement the model are readily obtained, and the model is relatively easy to apply (appendix 3).

Model Applications and Limitations

Our recommended model is based on data from the Transverse Ranges of Southern California and is therefore only applicable to this region. In order to accurately reflect conditions in watersheds used to develop the model, analyzed watersheds should be smaller than 30 km^2, urban development should be minimal in the headlands of the watershed, and expected sediment yields should be less than about 100,000 m^3. The prediction interval for potential sediment yields should be used to determine the range of potential sediment yields that a watershed can produce. Site-specific investigations, and knowledge of the history and magnitude of large sedimentation events, could be used to finesse the result. In addition, other models that predict potential sediment yield may be used for comparison.

The development of empirical models that estimate sediment yields in the future will benefit from better records of storm-specific sediment yields. Records of the amount of material removed from debris-retention basins have improved over time; however, many factors may lead to erroneous estimates of sediment yield in debris-retention basins. Uncertainty regarding how much material was present in a retention basin prior to a large event, or removing more material than was deposited by an individual storm, often contributes to inaccurate volume measurements.

If the sediment yield determined by cleaning out a debris-retention basin reflects material deposited by several storms, it is necessary to infer the amount of material deposited by each storm from the total volume. Error in these data develops when dividing sediment yield among several storms. Rather, sediment yields should be determined immediately following sediment-producing storms. If this is not feasible, dates of storms that cause runoff and sediment deposition should be recorded.

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Appendix 1. Data Used To Develop Multiple Regression Models

The following links can be used to view the data used in this study.

Single Event Volume Database

Divided Volume Database

Validation Database

Appendix 2. Statistics for Multiple Regression Models

Model 1

```
The regression equation is
log(V) = 2.19 + 0.661 log® + 0.113 √B + 0.327 LE + 0.462 log(A) + 0.016 S - 2.10 RR


Predictor                       Coef   SE Coef      T      P
Constant                      2.1929    0.1986  11.04  0.000
R                             0.6608    0.1289   5.13  0.000
```

√B	0.1127	0.0432	2.61	0.010
LE	0.3271	0.1037	3.16	0.002
Log(A)	0.4618	0.0750	6.16	0.000
S	0.0161	0.0025	6.43	0.000
RR	-2.0981	0.3920	-5.35	0.000

S = 0.527842   R-Sq = 49.0%   R-Sq(adj) = 48.2%

PRESS = 106.742   R-Sq(pred) = 46.94%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	6	98.652	16.442	59.01	0.000
Residual Error	368	102.531	0.279		
Total	374	201.183			

Model 2

The regression equation is
log(V) = 0.92 + 0.56 log(A) + 0.12 √B + 0.34 LE + 0.93 log(R) + 0.07 DD - 0.02 CC

798 cases used, 4 cases contain missing values

Predictor	Coef	SE Coef	T	P	VIF
Constant	0.9149	0.2108	4.34	0.000	
A	0.55546	0.03982	13.95	0.000	1.809
√B	0.12154	0.02911	4.18	0.000	1.656
LE	0.34411	0.08219	4.19	0.000	1.139
log(R)	0.9324	0.1262	7.39	0.000	1.042
DD	0.06510	0.01229	5.30	0.000	1.108
CC	-0.018263	0.003623	-5.04	0.000	1.110

S = 0.601457   R-Sq = 44.1%   R-Sq(adj) = 43.7%

PRESS = 290.931   R-Sq(pred) = 43.20%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	6	226.055	37.676	104.15	0.000
Residual Error	791	286.145	0.362		
Total	797	512.200			

Appendix III. Application of Model 1 To Generate Maps

Model 1 can be used to generate maps that describe potential volumes of sediment that may be deposited at the mouth of a watershed. The only data needed to implement the model are a DEM, a burn perimeter from the most recent fire to affect the watershed, and some information regarding potential rainstorms.

To determine the parameters of the variables included in model 1, basins of interest should first be delineated using the watershed tool in ArcGIS 8.0©. A slope map can be derived from the DEM using surface analysis tools in the spatial analyst. Using zonal statistics in ArcGIS 8.0©, the parameters for average watershed slope, watershed area, and watershed area burned by the most recent fire can be determined. These variables should be in units of percent and km^2. The lingering effect is calculated using the time since the most recent fire in years and the following equation:

$$\text{Lingering Effect} = e^{(-0.5\times\text{Years since most recent fire})}$$

Relief ratio is determined using ArcGIS 8.0 by measuring the distance of the longest channel extended to the drainage divide by the relief of the channel. The storm rainfall total (mm) can be estimated based on a design storm or according to different storm return intervals using a precipitation frequency atlas (for example, Miller and others, 1973).

To calculate potential sediment yield volumes generated by a watershed a user must incorporate the parameters into the equation for model 1 (eq. 2 in text).

The calculated volumes represent the amount of material that may flow from the mouth of a basin. These estimates are in units of log m^3 which should be transformed to represent a mean estimate of sediment yield in m^3. A prediction interval can be determined by adding and subtracting the residual standard error, S, (0.52) to and from the volume estimate (in units of log m^3). The model results can be represented in the form of a hazard map by displaying the basins according to their predicted estimates of sediment yield.

Due to limitations of the data used to develop the model, the model should not be used if expected volumes exceed 80,000 m^3 or for watersheds larger than 30 km^2. If it is necessary to determine potential sediment yields from basins larger than 30 km^2, the watershed can be divided into several tributaries to calculate volumes for each tributary. Mean values for sediment yield can be summed from each of the tributary watersheds to provide a total sediment yield for a larger watershed.