Comparison of Sediment Load Models in Predicting Sediment Deposition Patterns in Streams of the Sierra Nevada and Central Coast of California

Report 2 of 4

Contract # 05-179-160-0

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Executive Summary

Different modeling approaches have been developed to predict erosion and sediment delivery to streams based on landscape features that incorporate land use disturbance, topography, geology, and climate. We evaluated the ability of three of these models (FOREST; AGWA; RUSLE) to estimate sediment deposition in 98 streams in the Sierra Nevada and central coast region of California where survey data was gathered on bed substrate particle size distributions and other channel geomorphic features. These models differ in the theory and mechanics that the models are based on. Since RUSLE and FOREST do not account for transport and deposition of sediment in the stream channel, we adjusted their output by distributing by upstream channel length and normalizing by an index of stream power. We found that this adjustment greatly improved correlations with observed sediment. Estimates of erosion production and sediment yield from the FOREST model had the strongest correlations with observed sediment deposition in both the Sierra Nevada and central coast streams. FOREST provides explicit estimates of road-related erosion and these yields alone at either the riparian or whole-catchment scale were also correlated with stream bed deposition. RUSLE sediment estimates had moderate correlations with observed sediment in the Sierra and central coast, and AGWA sediment delivery estimates had less to no correspondence with observed sediment levels in the central coast and Sierra Nevada. On average, sediment estimates from all model output were 1.25 to 5 times higher for test populations than for reference populations. Further refinement and calibration of FOREST, RUSLE, and AGWA, including developing the capability of these models to incorporate sediment deposition estimates for stream reaches, could potentially produce even more accurate relationships between sediment loads and bed deposits.

INTRODUCTION

Direct field measurements of turbidity, total suspended solids, sediment traps, and stream substrate composition have been used to quantify local erosion and sediment loading in streams but these are difficult to relate to whole watershed processes. Alternatively, sediment load dynamics can be estimated remotely using models of erosion processes at varied spatial scales. The increasing availability and use of basic landscape measures in a Geographic Information System (GIS) have lead to the development of a variety of GIS-based erosion and sediment load modeling approaches. Many of these models are based on equations for calculating soil erosion, such as the Universal Soil Loss Equation (USLE) and its revised versions, Revised USLE (RUSLE) and Modified USLE (MUSLE). The USLE estimates average soil loss over time as a product of five factors: rainfall erosivity index, soil erodibility, slope length and steepness, land cover management, and support practice factor (Wischmeier and Smith 1965; Wischmeier and Smith 1978). These factors can be computed in a GIS using widely available spatial data such as climate, soil, geology, topography, hydrology, land use, and land cover data. Although USLE was designed for, and used most widely, in estimating erosion from agricultural lands, efforts to modify USLE for use in watersheds that are more topographically complex and with a higher diversity of land uses have lead to the development of erosion models such as the Automated Geospatial Watershed Assessment (AGWA) and the RUSLE model. Some models not only calculate soil erosion, but they also simulate the transport of eroding soil down hillslopes and into stream channels by incorporating hydrological modeling, such as the Soil and Water Assessment Tool (SWAT) and the Water Erosion Prediction Project (WEPP). Sediment load models have also been developed to meet specific needs. For example, AGNPS (AGricultural NonPoint Source pollution model) was designed to evaluate the effects of particular land use disturbances in predicting sediment and nutrient loads from agricultural landscapes. FOREST (FORest Erosion Simulation Tools) was designed to model erosion in forested environments.

Erosion and sediment load models are now commonly used as watershed assessment tools (Abdulla and Eshtawi 2007; Semmens and Goodrich 2005; Semmens et al. 2006). However, studies have found that some models based on USLE fail to predict observed sediment yield and warn users to be cautious if using model results for management decisions (Boomer et al. 2008; Kinnel 2005). Such studies have attempted to evaluate the ability of erosion models to predict observed sediment yield, as suspended sediment), but few (if any) have evaluated the ability of sediment yield estimates from erosion models to predict sediment deposition in streams. We compared three erosion and sediment load models that rely on different assumptions and have different methods of estimating stream sediment dynamics: Forest Erosion Simulation Tools (FOREST), Automated Geospatial Watershed Assessment (AGWA), and the Revised Universal Soil Loss Equation (RUSLE). We evaluated the ability of these models to predict observed sediment deposition in 74 streams in the Sierra Nevada Mountains and 24 streams in the central coast region of California in order to address the following questions:

1) How well do these erosion and sediment load models predict observed sediment deposition in streams, and for different regions?

2) Which field measurements of in-stream sediment deposition are best predicted by erosion and sediment load models?
3) Do models estimate higher amounts of sediment in streams designated as ‘disturbed’ rather than ‘reference’ (using standard reference and test designations based on roads)?
4) Do models improve on simple GIS land use percent or road density in relation to observed sedimentation levels in streams?

METHODS

Physical Habitat Surveys of Reach Geomorphology

We conducted physical habitat surveys of reach geomorphology at a total of 98 sites, 74 in the Sierra Nevada and 24 in the central coast range. Methods of physical habitat surveys are described in the first report, "Development of Sediment TMDL Guidance Indicators: Relation of roads and land use disturbances at different spatial scales to the depositional environment of streams in the Sierra Nevada and Central Coast of California" (Herbst et al. 2011).

Reference-Test/Dose Designations

Sites were partitioned into reference and test groups by identifying breaks or discontinuities in site distributions for co-plots of road density and road crossings in the Sierra, and road density and catchment human land use in the coast range. We defined reference sites in the Sierra as those with road density within a 100 m buffer each side of the stream of less than about 1.0 km/km^2 and upstream road crossings less than 0.4 crossings/km (Figure 3 of report 1). In the coast range, limits were set using mixed criteria of riparian roads $\leq$3.0 km/km^2 and $\leq$10% combined human land uses within the catchment (Figure 4, report 1). Detailed methodology for selection, and listings of stream sites are presented in report 1.

Erosion and Sediment Loading Models

FOREST, AGWA, and RUSLE are quasi-distributed models that implement Geographic Information System (GIS) software and use readily available GIS data. These models either represent a watershed on the landscape as a group of sub-watersheds or as a grid of equally sized cells. Each model uses different methods to simulate erosion and estimate erosion on a cell by cell basis (or sub-watershed by sub-watershed). These erosion estimates account for erosion from both natural and anthropogenic sources and are based on GIS data such as topography, climate, soils, roads, land cover, historic land use, and disturbances. Once an estimate of erosion production has been calculated, some models (FOREST and AGWA) then attempt to route the eroded sediment down slope across the landscape from cell to cell. The amount of sediment that is either deposited or transported from one cell to the next is also based on GIS data such as topography, climate, land cover, and soils. These types of models typically can provide two main sediment estimates for a stream reach: erosion production and sediment delivery. Erosion production is the gross amount of erosion occurring in all cells upslope of a stream reach. Sediment delivery is the net amount of sediment produced upslope that is transported across the landscape and is eventually delivered to a stream reach. Erosion production and sediment delivery are reported as annual averages (e.g. Megagrams per year). Basic differences between FOREST, AGWA, and RUSLE are presented in Appendix A.

FORest Erosion Simulation Tools (FOREST)

The FOREST model calculates changes in sediment regime due to the cumulative effects of natural and anthropogenic disturbances to watersheds in forested landscapes (Litschert 2009). FOREST was designed to compare spatially-proximate watersheds, typically for a temporal contrast (e.g., before and after logging or fire). The model output provides a yearly estimate of total erosion production and sediment delivery, as well as separate estimates of production and delivery from roads.

We used the following input data for FOREST: 30-meter Digital Elevation Model (DEM); stream locations from National Hydrology Dataset; Road data from Topologically Integrated Geographic Encoding and Referencing (TIGER) dataset produced by the U.S. Census Bureau; Fire Perimeter data from the California Department of Forestry and Fire Protection (FRAP); Forest Harvesting data from the Forest Service Activity Tracking System (FACTS); and soil data from State Soil Geographic (STATSGO).

In FOREST, erosion production was estimated from natural sources as well as from each type of disturbance present in a watershed. We assigned the default background level of erosion production as a fixed constant in proportion to the catchment area (0.1 Mg/ha/yr). For each disturbance type, it is possible to input detailed information specific to a particular disturbance type, such as the erosion rate, disturbance intensity, and recovery time. We used FACTS forest harvesting data to estimate impact and recovery from logging activities, and FRAP data to estimate sediment impact and recovery from forest fires. FOREST also requires an input for fire severity, which was not available at the time of analysis. As a proxy, we assigned fire severity classes to the Fire Perimeters dataset by overlaying FRAP's Fire Threat dataset, which assigns areas to fire threat rankings based on topography and vegetative fuels. We assigned logging sedimentation rates to each forest harvest activity type based on values established by different Forest Service units in the Sierra Nevada (Menning et al. 1997). We were not able to use logging as a model input for the central coast sites because logging there is nearly entirely a private enterprise and public data is not available. The result is a combined estimate of erosion production from logging, fire, and natural sources. However, logging and fire were uncommon in our study watersheds and so their contribution to erosion production in this study was negligible.

FOREST then uses the Water Erosion Prediction Project (WEPP) model to calculate the percent of erosion production that is 'delivered' from each grid cell to the next downslope cell based on landscape characteristics of topography, soil type, land cover, and climate (known as a spatially-distributed model). Soil type was determined from STATSGO data, in which each grid cell was designated as either clay and silt loam or sandy loam based on K-factors (soil detachability). The K-factor threshold for designating soil type as either clay-silt loam vs. sandy loam was determined from empirical evidence (Costick 1996). Climate data was derived from climate files created using a WEPP interface created by the National Soil Erosion Research Laboratory (NSERL), a unit of the U.S. Department of Agriculture. One central climate condition was selected for the Sierra Nevada, and two for the Central Coast - one for high precipitation coastal areas, and one for inland sites in the eastern coastal rain-shadow. The WEPP interface assigned an expected sediment response for each pixel configuration based on a weather generation system and regional climate data. These landscape characteristics determine how much of the sediment produced in a cell is actually delivered to a stream. The output, called "FOREST Hillslope sediment delivery," is the sum of sediment delivered from all upslope grid cells.

Road erosion production and sediment delivery was modeled separately from other disturbances using the approach of Luce and Black (1999). Erosion production from roads was calculated based on the product of the road slope X (length of road segments)^2 and a coefficient (717 used as default), referred to here as "Catchment Road Erosion Production". Since the delivery of erosion from roads to streams was not explicitly modeled, we made an assumption that erosion produced within a 200 meter stream zone is the fraction actually entering the stream. This sum of erosion produced within a 200 meter stream zone from roads is referred to here as "FOREST Riparian Road Erosion Production." The sum of sediment delivery from logging, fire, and natural sources ("FOREST Hillslope sediment delivery" and sediment delivery from roads ("FOREST Riparian Road Erosion Production") is the "FOREST Total Sediment Delivery" for each site.

Revised Universal Soil Loss Equation Model (RUSLE)

We used GIS-based models, the Revised Universal Soil Loss Equation model (RUSLE) and the Spatially Explicit Delivery Model (SEDMOD), to calculate soil erosion and sediment delivery. The Revised Universal Soil Loss Equation is a widely used standard method for estimating soil erosion (Renard et al. 1997):

$$A = R * K * LS * C * P$$

Where: A is the estimated soil loss (erosion) per year. R is the rainfall erosivity, K is the soil erodibility factor, LS is the topographic factor of slope length and steepness, C is the cover and land management factor (modified according to NLCD land cover class from a look-up table), and P is the support practice factor (this was set to 1 since we did not know where or how erosion management practices were being used). In the RUSLE model, soil erosion is calculated for each cell in a watershed and then summed as the average erosion production, referred to here as "RUSLE Erosion Production."

SEDMOD calculates sediment delivery based on a Sediment Delivery Ratio (SDR) (Ouyand et al. 2005). The SDR is calculated as:

$$SDR = 39\ A\ –1/8 + \Delta\ DP$$

Where: SDR = sediment delivery ratio. A = area of watershed. Δ DP = difference between the composite delivery potential and its mean value. The delivery potential layer is calculated as:

$$DP = (SG)r(SG)w + (SS)r(SS)w + (SR)r(SR)w + (SP)r(SP)w + (ST)r(ST)w + (OF)r(OF)w$$

Where: SG is the slope gradient. SS is the slope shape. SR is the surface roughness. SP is the stream proximity. ST = soil texture. OF = overland flow index. r = parameter rating (1-100). w = weighting factor (0-1).

Sediment Yield (or delivery) is calculated as:

$$SY = A * SDR$$

Where: SY = sediment yield (or delivery). A = gross soil erosion. SDR = sediment delivery ratio. Sediment yield is calculated for each cell in a watershed. The summed sediment yield from all cells in a watershed is the total sediment yield for a watershed, referred to as "RUSLE Sediment Delivery." RUSLE output thus is not spatially-distributed, as cells are not linked, only summed.

We used the following input data for RUSLE: a 30-meter DEM, stream locations from NHD, land cover from NLCD 1992, and soil data from STATSGO2. RUSLE used the DEM to determine runoff network and slope steepness; the NHD to create a network for analyzing the amount of yearly sediment that is delivered to streams; the NLCD to determine the ability of each pixel to produce and/or capture water and sediment; and STATSGO2 data to create a matrix of physical soil properties for each watershed. RUSLE provides climate files that were used to estimate the rainfall intensity factor.

Automated Geospatial Watershed Assessment (AGWA)

AGWA2 is an interface for performing spatially-distributed (cell- or grid based linkages simulating transport paths) hydrologic models, and was developed by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Agriculture (USDA) (Burns et al. 2007). AGWA2 implements two existing models, the Soil and Water Assessment Tool (SWAT) and the Kinematic Runoff and Erosion Tool (KINEROS2). SWAT is more appropriate than KINEROS2 for this study as it is a long-term sediment yield model without watershed size limits.

SWAT calculates a variety of output factors for each watershed, including total sediment delivery – defined as the annual amount of sediment in metric tons that is transported from the basin and routed as the bedload and suspended load through the stream network into the reach segment. Sediment calculations are made using the Modified Universal Soil Loss Equation (MUSLE):

$$Sed = 11.8 * (Q_{surf} * q_{peak} * area)^{0.56} K * LS * C * P * CFRG$$

Where: *Sed* is the sediment yield per time, *Qsurf* is the volume of surface runoff (mm H_2O/ha), *Qpeak* is the peak runoff rate (m^3/s), *area* is the area (ha) of hydrologic response unit, *K* is the soil erodibility factor, *LS* is the topographic factor of slope length and steepness, *C* is the cover and land management factor (modified according to NLCD land cover class from a look-up table), *P* is the support practice factor (this was set to 1 since we did not know where or how erosion management practices were being used). , *CFRG* is the coarse fragment factor and is calculated as:

$$CFRG = exp (-0.053 * \% \text{ rock in the uppermost soil layer})$$

In SWAT, the volume of surface runoff (*Qsurf*) is calculated using a modified Curve Number approach based on the following equation (Arnold et al. 1996):

$$Qsurf = (R – I_a)^2 / R - I_a + S$$

Where: *Qsurf* is the total surface runoff (mm), *R* is the daily rainfall (mm), I_a is the initial abstraction such as infiltration and interception prior to runoff (mm), *S* is the retention parameter based on the combination of soil, land use, and land cover. Estimates of I_a and *S* are derived from AGWA look-up tables.

The sediment yield is then routed through the stream network by segment, in which assumed changes in hydraulic geometry of channels are used to determine the fraction transported downstream as bedload and suspended load (Neitsch et al. 2002).

The following input data were used for implementing AGWA2: 30 meter DEM, land cover from NLCD 1992, Soil data from STATSGO2, and precipitation data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM). AGWA2 used the DEM to determine drainage delineation, runoff direction, slope length, and slope steepness; NLCD to determine the ability of each pixel to produce and/or capture water and sediment; STATSGO2 data to determine the erodibility and permeability of each pixel; and PRISM data to determine runoff and transmission of water and sediment. This model was also designed to compare temporal changes within, or in spatially-proximate watersheds. Comparing sites scattered throughout our 2 large study areas required combining sites into climate groups (suggested during contact with AGWA2 developers). Sites were pooled according to proximity to Weather Generation Stations (WGN), a climate network provided by AGWA2. This resulted in 4 climates for the Central Coast, and 6 for the Sierra Nevada.

AGWA2 does not specifically account for road erosion production, except for roads that are large enough to appear as an NLCD class. Since road erosion production is the main source of anthropogenic sediment in forested watersheds, we overlaid the NLCD data with road data from the Topologically Integrated Geographic Encoding and Referencing (TIGER) dataset produced by the U.S. Census Bureau.

Model Normalization

RUSLE and FOREST both do not account for transport and deposition of sediment routed through the flowing stream channel. Sediment delivery estimates from RUSLE and FOREST are simply a sum of sediment delivered from the catchment without taking into account the influence of fluvial processes in a stream channel. As a first approximation, in order to 'distribute' the sediment delivered from the catchment equally across stream channels, we divided the erosion production and sediment delivery estimates by the total length of upstream channel. To account for local hydraulic processes operating on the sediment delivered to the stream channel, we normalized sediment estimates by a reach-scale index of stream power (the product of average reach bankfull area in square meters and average percent slope). Sites of differing channel geometry and slopes could thereby be equitably compared to one another in terms of how sediment load exposure would be transported or deposited.

AGWA differs from RUSLE and FOREST in that it does account for sediment transport and deposition in the stream channel. Therefore, we did not distribute or normalize the sediment yield estimate from AGWA.

RESULTS

We found that sediment load estimates from FOREST had the most consistent correlations with observed sediment deposition in both the Sierra and central coast, the RUSLE model had moderate correlations, and AGWA only had moderate correlations in the central coast and no correlation in the Sierra (Tables 1 and 2; Figures 1 and 2). Sediment estimates from FOREST, AGWA, and RUSLE all made better predictions of sediment deposition for streams of the central coast than for streams in the Sierra Nevada.

FOREST, AGWA, and RUSLE showed higher correlations with reach wide deposition measures from point-intercept transects such as %FS, %FSG8, %FSG16, and D50, than with measures taken on depositional bars such as Bar %FS and Grid %FS. Thalweg measures of sediments were intermediate in correlating with sediment estimates from FOREST, AGWA, and RUSLE. Embeddedness in the Sierra had moderate correlation with outputs from FOREST but not the other models, while AGWA showed a better relationship in central coast streams than the other models. FOREST model outputs also showed correlation with excess FS, the level of fines and sand in excess of a regression of reference site FS on expected particle size (see report 1).

For streams from both regions, FOREST Catchment or Riparian Road Erosion Production had high correlations with many physical habitat measures of sediment (Tables 1 and 2, Fig.s 1-3). Plots and correlation coefficients also showed good correspondence of deposition levels with background hillslope sediment by itself, and with the total sediment delivery estimate, which incorporates all sources. The same was true of coastal streams, where all FOREST model outputs were even more strongly correlated with observed sediment levels.

In the Sierra and in the coast sites, the erosion production and sediment delivery terms from RUSLE give similar correlations to stream sediment deposits, suggesting that yield and delivery may be proportional across streams. RUSLE showed correlations better than 0.5 only for D50 in the Sierra, but included fine, sand and gravel correlations in coast streams.

On average, sediment estimates from all model output were 1.25 to 5 times higher for test populations than for reference populations (Table 3). The yields from FOREST and RUSLE, divided by stream length and stream power, gave absolute estimates that differed by 2 orders of magnitude, even though these were in the same units. Yields from AGWA were higher yet, though not precisely in the same units.

DISCUSSION

Representing cumulative watershed effects (CWEs) by sediment load models has become a valuable tool for evaluating land use management, but output from few of these models have previously been examined in relation to the depositional environment of streams. Using model outputs adjusted to distribute catchment sediment yields over the length of the stream channel network and accounting for reach-specific stream power differences, we found that predicted sediment loads from FOREST were in most cases correlated with stream bed deposition. Our results suggest that the sediment estimates from the FOREST model may be useful in accounting for CWEs, and can provide another means of relating disturbance to the deposition that degrades stream habitat across varied catchments. However, how the model accounts for the effect of roads separate from hillslope processes and other disturbances need to be reconciled. Calibration of differences in background erosion rates are needed for more accurate modeling between watersheds with differing environments. Assumptions about transport of road-derived sediments depend on stream proximity, and are at variance with the spatially-distributed process of hillslope transport, so should be modeled in the same way. How sediment loads move through streams have not yet been integrated, but we found simple standardizing according to upstream channel length and local stream power were effective in producing correlations with reach-scale deposition patterns.

We evaluated the ability of FOREST, RUSLE, and AGWA to provide estimates of sediment deposition in stream reaches. However, these models currently only provide estimates of sediment yield, which is not necessarily equivalent to sediment deposition. The sediment delivery estimated by FOREST and RUSLE is the amount of sediment that is delivered to the stream channel that then could be either deposited in the stream channel or carried out of the watershed entirely as bedload or suspended sediment. The sediment delivery estimated by AGWA differs from FOREST and RUSLE in that it is an estimate of the bedload and suspended sediment that is transported out of the watershed entirely. AGWA sediment delivery excludes sediment that is deposited in the stream channel. Clearly these models could be improved so that they provide estimates of spatially explicit sediment deposition throughout stream channel networks. Sediment deposition is calculated as part of the sediment routing modeled in SWAT, but AGWA does not currently make this measure available to users (Arnold et al. 1996). FOREST also has the potential to route sediment through the stream channel and provide estimates of sediment deposition, but this function of FOREST is still under development (Litschert 2009).

The sediment load models compared here differ in several important respects. Although RUSLE and AGWA are both based on the Universal Soil Loss Equation (USLE) for predicting sediment yield from hillslopes, they differ in how they calculate factors of USLE (Ward and Trimble 2004). RUSLE uses regional annual rainfall intensity in effect, to mobilize sediment, and AGWA improves upon this by instead modeling surface runoff according to daily timesteps and local precipitation. These models further apply coefficients to simulate the relative differences in erosion rates due to different land use cover. FOREST applies only a fixed constant to background erosion production, so is not reliable in estimating natural sediment yield. FOREST does account for how this sediment is delivered to stream channels, so it may still provide a reasonable approximation of relative inputs assuming that initial sediment produced is the same across all landscape conditions.

Neither RUSLE nor AGWA separately distinguish sediment produced and delivered from roads. Instead, RUSLE and AGWA only account for road erosion production when roads are significant enough to appear in the NLCD. We attempted to enhance how AGWA incorporates roads in its disturbance modeling by altering the NLCD to reflect all roads that are depicted by the TIGER roads dataset. The FOREST model incorporates a road sediment module that accounts for road slope, length, and stream proximity to estimate erosion production, and also models the effects of logging and fires. Though FOREST is useful in estimating road, fire, and logging disturbances that dominate in forested landscapes (as the acronym implies), it does not evaluate the influence of other land uses, such as agriculture or impervious surfaces. The difference in the type of disturbances that are modeled by FORST, RUSLE, and AGWA may account for the variation in correlating with observed sediment deposition. Since roads are widely thought to be significant sources of erosion in forested mountain landscapes (Forman and Alexander 1998; Luce and Black 1999; Jones et al. 2000; MacDonald et al. 2004), and FOREST most directly accounts for erosion from roads, it seems reasonable that FOREST would provide the best correlations with observed sediment deposition in the predominately forested watersheds of the Sierra Nevada. Both AGWA and RUSLE primarily model erosion from human disturbances depicted in the NLCD. The Sierra

Nevada watersheds had little or no human disturbance land use (e.g. agriculture, development) while human land use cover in the central coast watersheds covered greater proportions of land area (over 40% in some cases). This difference in the proportion of human land use disturbance depicted in NLCD between the Sierra and coast sites may account for AGWA and RUSLE performing better on the coast than in the Sierra.

Though sometimes calibrated with field measurements to test accuracy and incorporate adjustment factors, attempts to validate the RUSLE sediment load model and derivatives have typically reported a failure to accurately predict sediment yields (Kinnell 2005). Small plot-scale predictions of erosion and agricultural soil loss using USLE often give accurate results, but scaling up to whole catchments has proven difficult. Adjusting sediment yield estimates to give stream inputs using sediment delivery ratios (as done in RUSLE and AGWA) have failed to predict total suspended sediment (TSS) load from catchments, as the correction terms do not appear to adequately account for the complexity and interactions of land use effects, soils, vegetation cover, and topographic variability (Boomer et al. 2008). Losses by deposition within the stream channel, especially in areas of low stream power, may also explain some of the discrepancy between estimates of sediment yield and measured suspended load. Using TSS as a response indicator to sediment yield should incorporate not only how deposition changes with stream power, but the load added through re-suspension of deposits and channel erosion. In this context, sediment rating curves (suspended transport with under varied flow levels) contrasting reference and test channels (stable vs. unstable) may provide better empirical relations to deposition in disturbed streams (Simon et al. 2004). The storage of sediment in streams and impoundments may account for much of the deficit in total suspended load transport measured at drainage outlets compared to estimates of land surface erosion (Renwick et al. 2005), though this was not a source of error in our study design where sites were selected that had no upstream reservoirs acting as sediment traps.

Sediment yield from catchments, distributed over the length of stream channels, and normalized by reach-specific stream power was used to compare among differing sites, and provided consistent predictions of sediment deposition found in streams in both regions of this study. This suggests that deposited rather than suspended sediments may provide an alternative measure of the cumulative load burden entering streams as modeled for different landscape conditions. Though loads from models showed correlation to deposition, and required standarizing to do so, there was still considerable variation, so understanding dynamics of sedimentation at any given site remains elusive. Because cumulative land use contribution to loads within whole catchments appears to be small, it was also difficult to apportion the influence of different disturbance sources to deposition. Without model refinements, simple measures of percent cover or road density may be more effective in predicting minimum sediment levels (refer to report 1).

RUSLE and FOREST do not account for transport and deposition of sediment in the stream channel. In order to account for the influence that fluvial processes would have on the sediment delivered to a channel, we divided model estimates by upstream channel length and by an index of stream power. The index of stream power (the product of average bankfull area in square meters and average percent slope) was derived from empirical data acquired from physical habitat field surveys. Without adjusting FOREST and RUSLE model output using empirical data from field surveys, spearman correlations with sediment estimates would be lower. Unadjusted FOREST outputs for FSG8 for example would have ranged from R= 0.023 to 0.287 in the Sierra (compared to R= 0.519 to 0.617) and from 0.252 to 0.604 in the coast (compared to 0.612 to 0.746). Similarly, unadjusted RUSLE FSG8 correlations in the Sierra were -0.402 to -0.355 (compared to 0.26 to 0.293) and -0.319 to -0.271 on the coast (compared to 0.497 to 0.512). This indicates that it may be necessary to adjust sediment estimates from FOREST and RUSLE using site-specific empirical field data in order for the models to adequately predict in-stream sediment deposition. Sediment delivery estimates from AGWA do not need adjustment because this model already accounts for in-stream routing in its estimates. However, it is of note that when AGWA sediment delivery is adjusted, its correlations with observed sediment deposition increase substantially.

Sediment estimates from some of the load models we evaluated had higher correlations with observed sediment deposition than GIS-derived measures of land use cover and roadedness (e.g. road density, road crossings, human land use influence, etc., see report 1), but this was true only when they were adjusted by upstream channel length and reach-scale stream power. Knowing the stream power, the vulnerability of a stream to elevated deposition could be adjusted not only for a given modeled load, but also for some level of land use disturbance. An adjusted land use model could be derived by dividing a land use measure (e.g. upstream road crossings) by the length of the channel, and then by an index of stream power (ratio of risk to counteraction). In this way, sediment deposition can be predicted with accuracy similar to FOREST (Table 4 and Figure 4). Although this approach does not produce a numerical estimate of sediment yield as the sediment load models do, it does combine readily-available field and GIS data to generate projections of potential sediment problems and does not require substantial computation time or technical expertise. Resource managers without the means to develop complex sediment load models such as FOREST, RUSLE, or AGWA may find the results from this more simple approach satisfactory for their needs.

Summary Conclusions and Report Findings:

- Our results suggest that the sediment estimates from the FOREST model are useful in accounting for cumulative watershed effects, and can be reliably related to the deposition that degrades stream habitat. However, with further refinements and local calibrations of FOREST, RUSLE, and AGWA (as suggested in model documentation), these models could potentially produce even more accurate estimates of sediment loads in streams.
- It is necessary to adjust the sediment estimates from FOREST and RUSLE by distributing by stream length and normalizing by a stream power index (derived from field surveys) in order to account for the influence of in-stream fluvial processes.
- Without adjusting FOREST and RUSLE to account for in-stream fluvial processes, correlations with observed sediment deposition are much weaker.
- An adjusted land use model can be developed by dividing a measure of land use (e.g. upstream road crossings) by the length of the channel, and then by an index of stream power. Sediment deposition can be predicted by adjusted land use models with similar accuracy to FOREST. Risk of erosion and sedimentation (land use, roads) relative to counteracting forces (stream power) provide a simpler approach than explicit load models to predicting sediment deposition.

		FS	FSG8mm	FSG16mm	D50	Emb	ThwFSG16	BarFS	GridFS	ExcessFS	RBS
FOREST	Catchment Road Erosion Production	0.582*	0.616*	0.619*	-0.654*	0.357*	0.504*	0.331*	0.381*	0.547*	-0.391*
	Riparian Road Erosion Production	0.497*	0.537*	0.543*	-0.558*	0.337*	0.467*	0.294*	0.35*	0.468*	-0.308*
	Hillslope Sed. Delivery	0.522*	0.519*	0.517*	-0.643*	0.248*	0.452*	0.351*	0.329*	0.495*	-0.389*
	Total Sed. Delivery	0.535*	0.533*	0.529*	-0.652*	0.256*	0.466*	0.358*	0.336*	0.505*	-0.389*
RUSLE	RUSLE Erosion Production	0.244*	0.292*	0.289*	-0.518*	0.150	0.132	0.069	0.078	0.228	-0.236*
	RUSLE Sed. Delivery	0.22*	0.259*	0.249*	-0.473*	0.155*	0.097*	0.081*	0.063*	0.208*	-0.25*
AGWA	AGWA Sed. Delivery	_-0.181_	_-0.173*_	_-0.169*_	_0.258*_	_-0.214_	-0.063	-0.144	0.035	-0.169	_0.250*_

Table 1: Spearman correlation coefficients for the sediment model results and physical habitat measures for the Sierra Nevada. Highlighted text indicates correlation coefficients greater than 0.5. Italicized text are coefficients in the opposite direction than hypothesized. Astrix (*) indicate significant correlation at the 0.05 level. Sediment estimates from FOREST and RUSLE are in Megagrams per year and were distributed (divided) by the upstream channel length and normalized (divided) by an index of stream power at each reach (bankfull area * slope). Sediment estimates from AGWA are in Megagrams per year.

		FS	FSG8mm	FSG16mm	D50	Emb	ThwFSG16	BarFS	GridFS	ExcessFS	RBS
FOREST	Catchment Road Erosion Production	0.690*	0.612*	0.578*	-0.541*	_-0.120_	0.449*	0.310	0.235	0.600*	-0.217
	Riparian Road Erosion Production	0.698*	0.613*	0.585*	-0.542*	_-0.132_	0.426*	0.307	0.307	0.625*	-0.243
	Hillslope Sed. Delivery	0.710*	0.745*	0.655*	-0.655*	_-0.208_	0.488*	0.248	0.202	0.555*	-0.317
	Total Sed. Delivery	0.702*	0.741*	0.657*	-0.648*	_-0.205_	0.498*	0.245	0.222	0.548*	-0.284
RUSLE	RUSLE Erosion Production	0.543*	0.512*	0.513*	-0.540*	_-0.119_	0.278	0.051	0.026	0.252	_0.102_
	RUSLE Sed. Delivery	0.511*	0.496*	0.492*	-0.520*	_-0.140_	0.283	0.012	0.008	0.227	_0.106_
AGWA	AGWA Sed. Delivery	0.317	0.314	0.304	-0.290	0.405*	0.321	0.307	0.123	0.258	_0.028_

Table 2: Spearman correlation coefficients for the sediment model results and physical habitat measures for the Central Coast. Highlighted text indicates correlation coefficients greater than 0.5. Italicized text are coefficients in the opposite direction than hypothesized. Astrix (*) indicate significant correlation at the 0.05 level. Sediment estimates from FOREST and RUSLE are in Megagrams per year and were distributed (divided) by the upstream channel length and normalized (divided) by an index of stream power at each reach (bankfull area * slope). Sediment estimates from AGWA are in Megagrams per year.

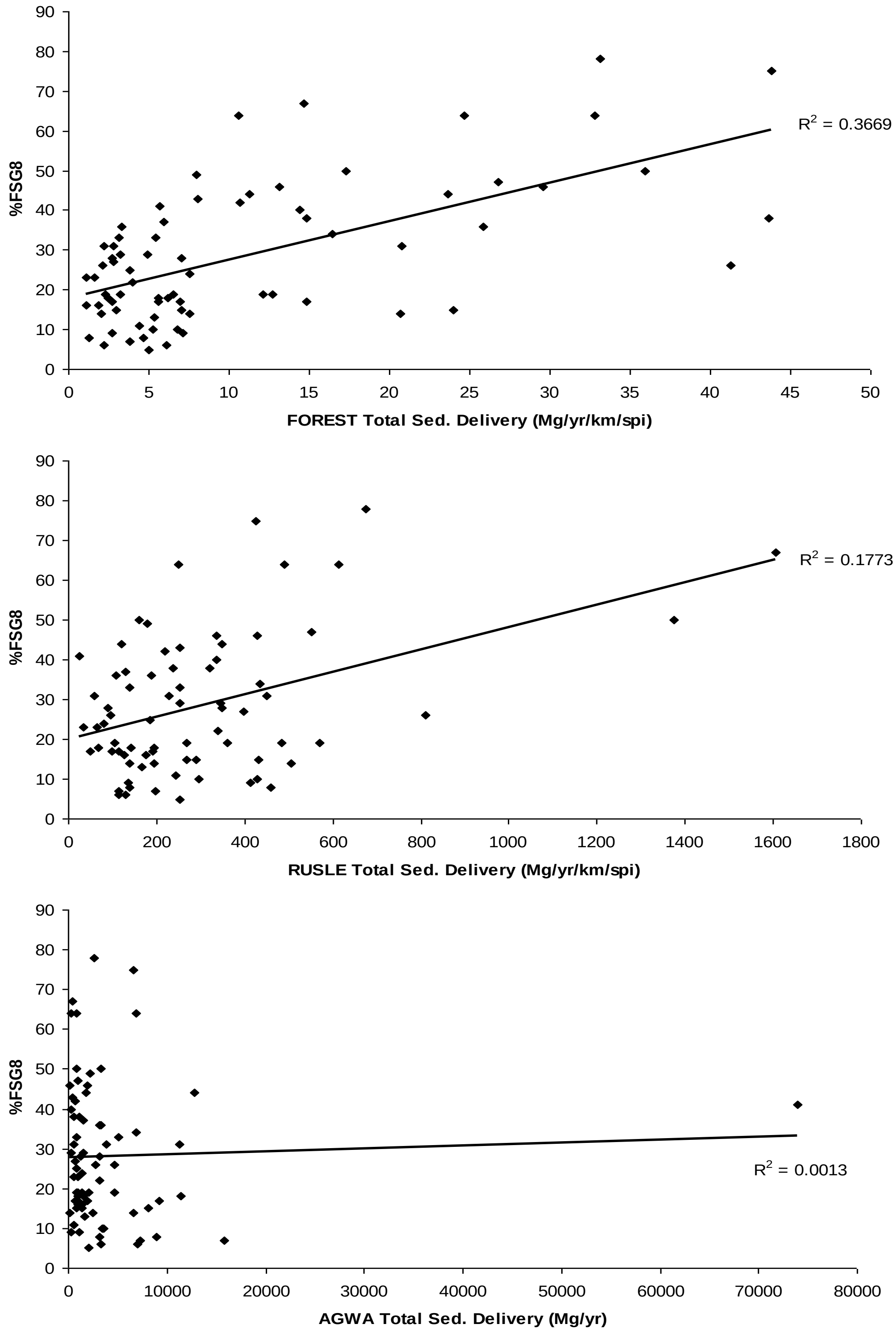


Figure 1: Contrasting estimates of total sediment delivery in relation to observed %FSG8 among models for the Sierra Nevada sites.

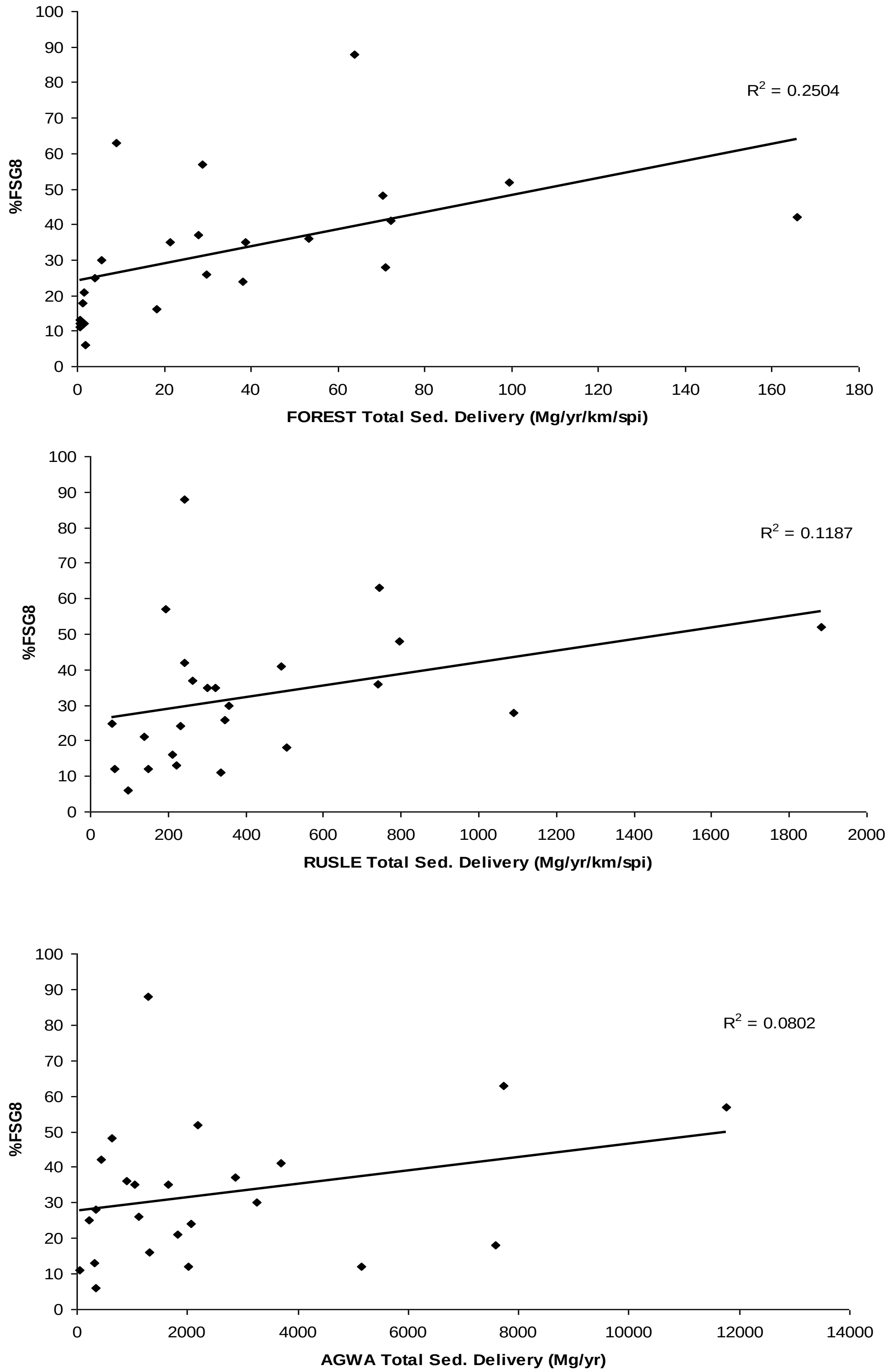


Figure 2: Contrasting estimates of total sediment delivery in relation to observed %FSG8 among models for the Central Coast sites.

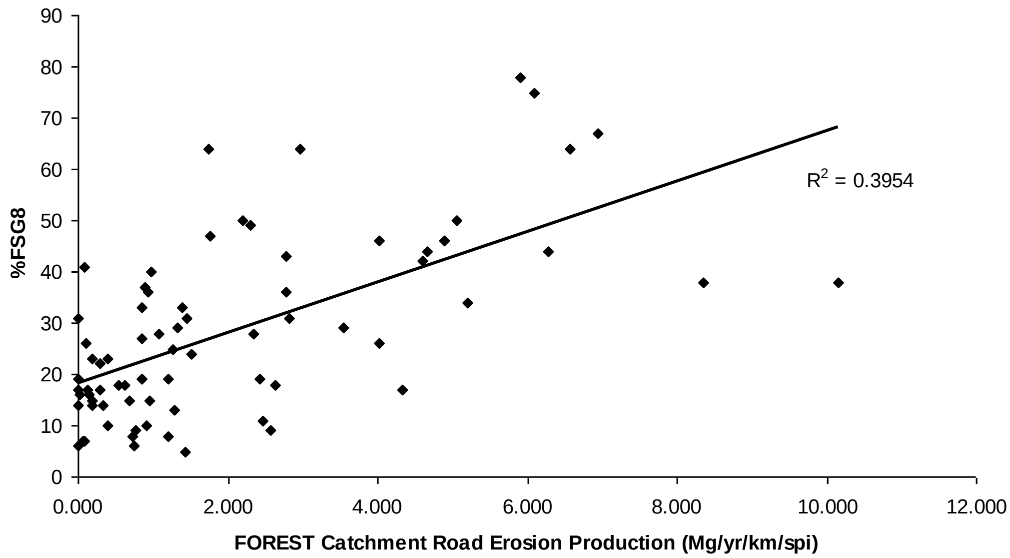


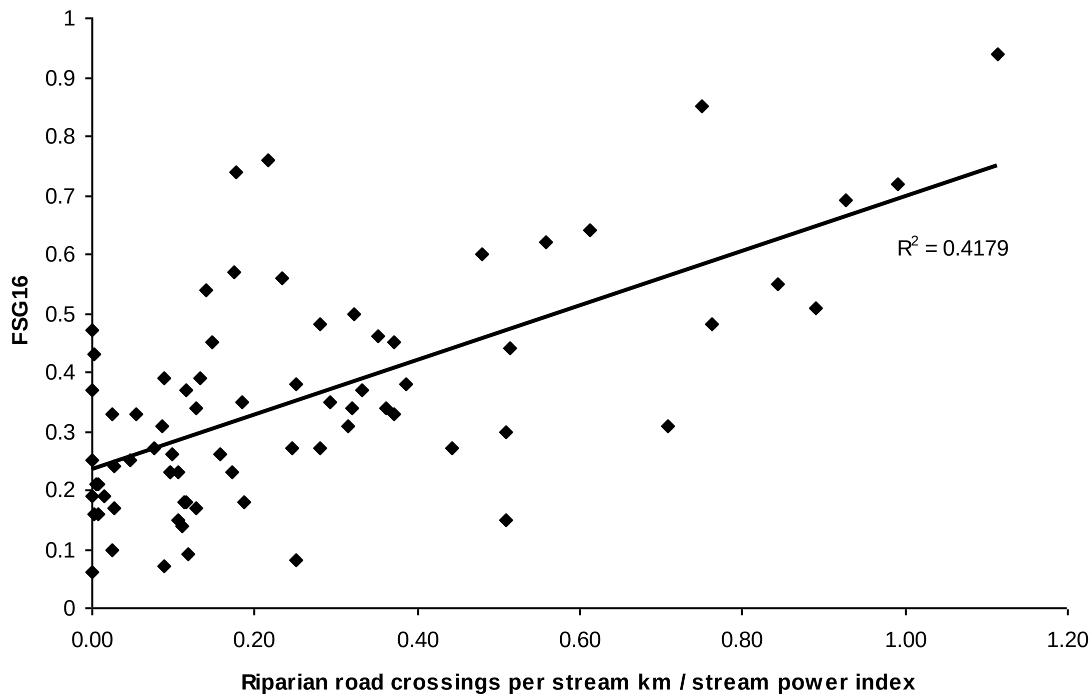
Figure 3: The relationship between FOREST Catchment Road Erosion Production and observed %FSG8 in the Sierra Nevada.

		Sierra Nevada		Central Coast	
		Reference	**Test**	**Reference**	**Test**
FOREST	Road Sed. Production	0.56	2.93	7.27	13.60
	Road Sed. Delivery	0.15	0.72	3.05	5.84
	Hillslope Sed. Delivery	7.88	11.73	18.27	46.85
	Total Sed. Delivery	8.02	12.45	21.32	52.69
RUSLE	RUSLE Sed. Estimate	1001.34	1355.52	1681.08	2141.39
	RUSLE Sed. Delivery	245.95	324.94	377.42	473.36
AGWA	AGWA Sed. Delivery	2737.41	4709.42	1886.01	3346.30

Table 3: Average sediment estimate from model output between reference and test populations for the Sierra Nevada and Coast Sites. Sediment estimates from FOREST and RUSLE are in Megagrams per year and were distributed (divided) by the upstream channel length and normalized (divided) by an index of stream power at each reach [(bankfull area * slope)/100]. Sediment estimates from AGWA are in Megagrams per year.

		FS	FSG8	FSG16	D50	Emb	ThFSG	BarFS	GridFS	Excess FS	RBS
Sierra	FOREST	0.58	0.62	0.62	-0.56	0.36	0.50	0.36	0.38	0.55	-0.31
	Adjusted Land Use Model	0.49	0.54	0.57	-0.57	0.32	0.51	0.33	0.35	0.45	-0.22
Coast	FOREST	0.71	0.75	0.66	-0.54	-0.12	0.50	0.31	0.31	0.63	-0.21
	Adjusted Land Use Model	0.66	0.65	0.71	-0.55	-0.12	0.54	0.33	0.21	0.49	-0.06

Table 4: Highest (max) spearman correlation for estimates of erosion and sediment delivery from the FOREST model (Catchment Road Erosion Production, Riparian Road Erosion Production, Hillslope Sediment Delivery, or Total Sediment Delivery) compared with highest spearman correlation for the adjusted land use model (Catchment Road Density, <u>Riparian Road Density, or Road Crossings</u>).



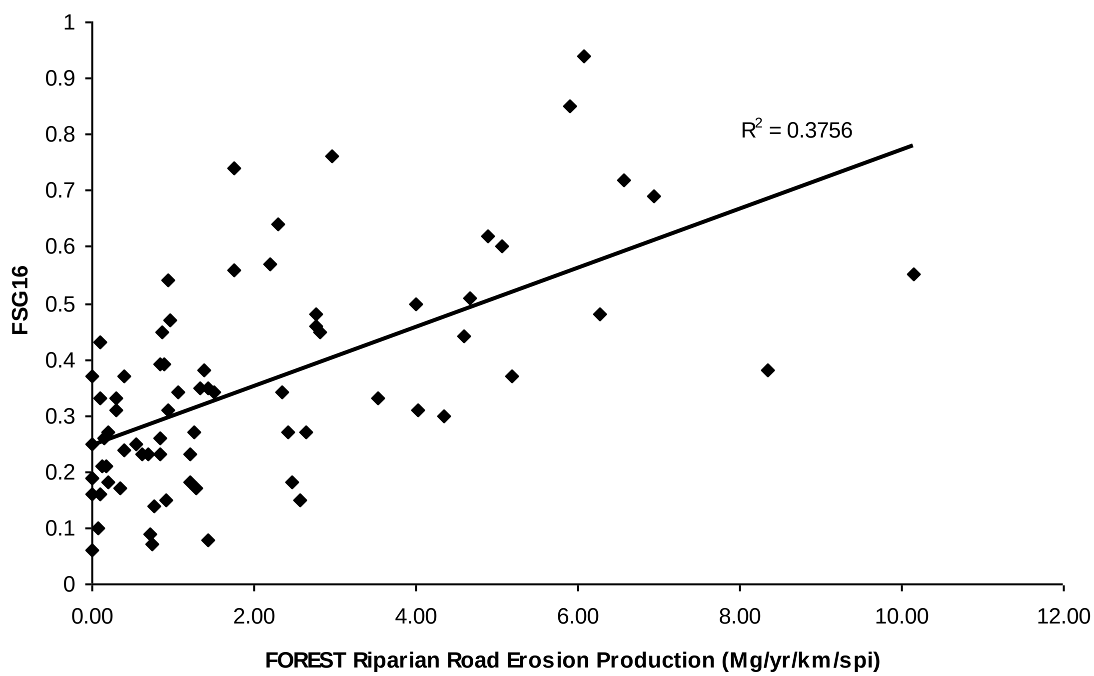
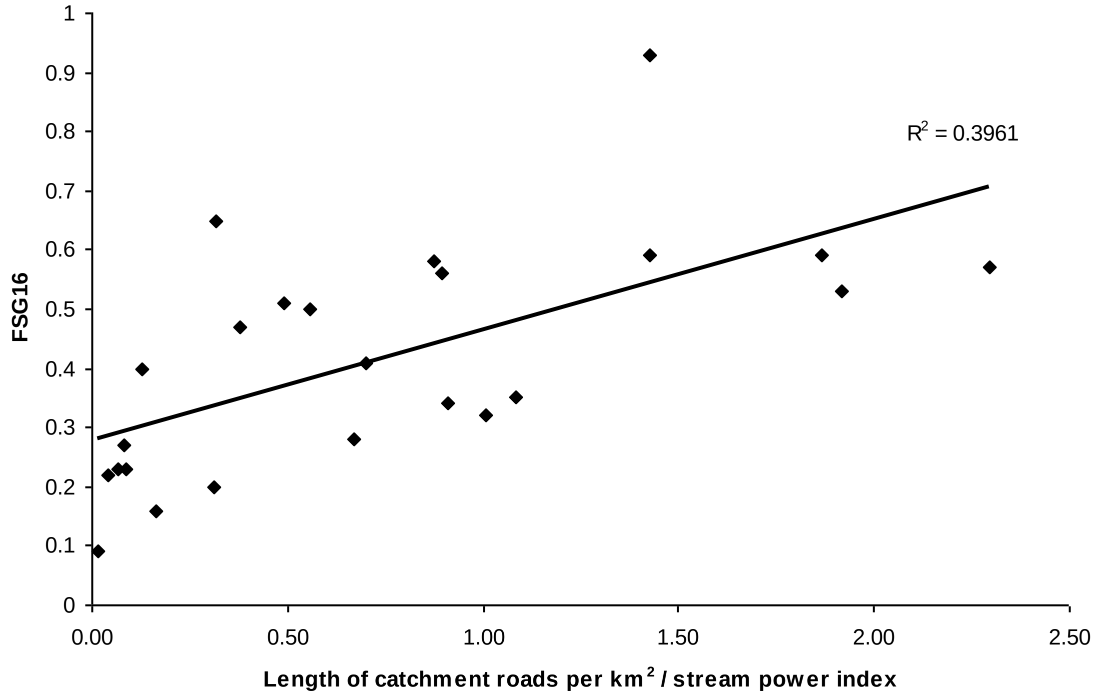


Figure 4: The relationship of %FSG16 and an adjusted land use model of riparian road crossings per stream km normalized by a stream power index compared with the relationship %FSG16 and FOREST Riparian road erosion production distributed by stream length and normalized by a stream power index for the Sierra Nevada sites.



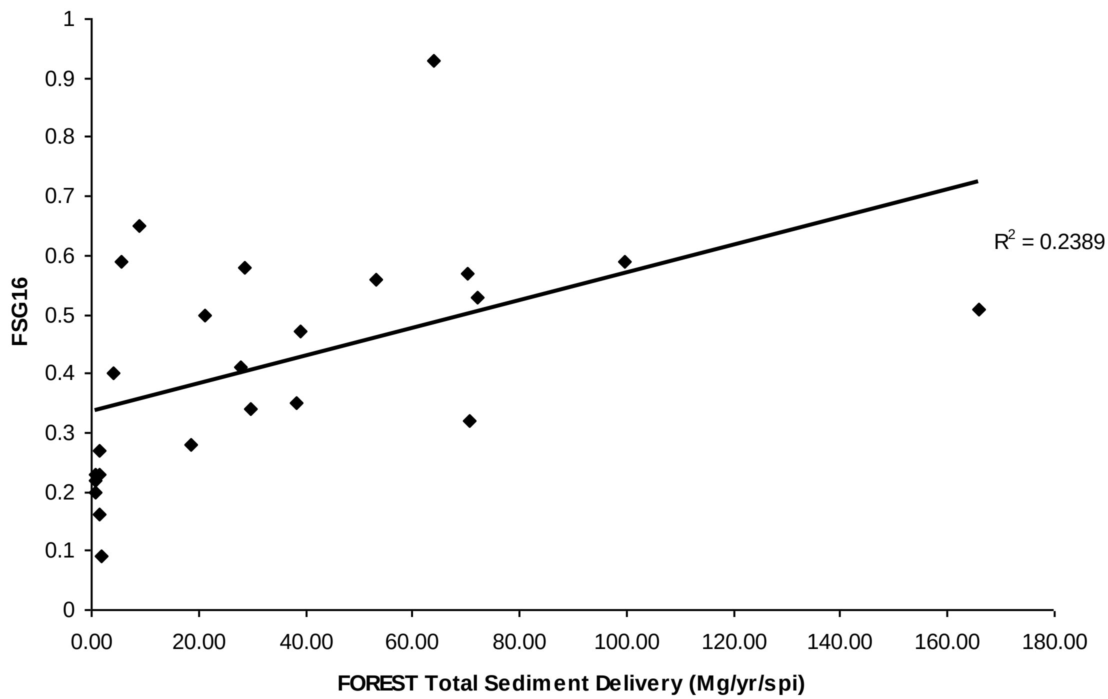


Figure 5: The relationship of %FSG16 and an adjusted land use model of the length of catchment roads per square km and normalized by a stream power index, compared with the relationship %FSG16 and FOREST total sediment delivery distributed by stream length and normalized by a stream power index for the Central Coast sites.

Acknowledgements:

We used a set of computational GIS scripts developed by Rick Van Remortel of Lockheed Martin Environmental Services to run RUSLE analyses for our study areas.

References

Abdulla, F. and T. Eshtawi. 2007. Application of Automated Geospatial Watershed Assessment (AGWA) tool to evaluate the sediment yield in a semi-arid region: case study, Kufranja Basin-Jordan. Jordan Journal of Civil engineering 1(3): 234-244.

Arnold, J.G., J.R. Williams, R.Srinivasan, and K.W.King. 1996. The Soil and Water Assessment Tool (SWAT) User's Manual. Temple, TX.

Boomer, K.B., D.E. Weller, and T.E. Jordan. 2008. Empirical models based on the Universal Soil Loss Equation fail to predict sediment discharges from Chesapeake Bay catchments. Journal of Environmental Quality 37:79-89.

Burns, I.S., S.N. Scott, L.R. Levick, D.J. Semmens, S.N. Miller, M. Hernandez, D.C. Goodrich, and W.G. Kepner, 2007. Automated Geospatial Watershed Assessment 2.0 (AGWA 2.0) – A GIS-Based Hydrologic Modeling Tool: Documentation and User Manual; U.S. Department of Agriculture, Agricultural Research Service. Available at http://www.tucson.ars.ag.gov/agwa/.

Costick, L.A., 1996. Indexing current watershed conditions using remote sensing and GIS. Sierra Nevada Ecosystem Project, Center for Water and Wildland Resources, University of California-Davis, Final Report to Congress, III. Davis, CA. pp. 79-152. http://www.ceres.ca.gov/snep/pubs/v3.html.

Curtis, J.A., L.E. Flint, C.N. Alpers, and S.M. Yarnell. 2005. Conceptual model of sediment processes in the upper Yuba River watershed, Sierra Nevada, CA. Geomorphology 68:149-166.

Forman, R.T.T. and L.E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29:207-231

Herbst, D.B. 2011. Development of Sediment TMDL Guidance Indicators: Relation of roads and land use disturbances at different spatial scales to the depositional environment of streams in the Sierra Nevada and Central Coast of California. Revised report to the State Water Resources Control Board, Sacramento, California, January 2011.

Jones, J.A., F.J. Swanson, B.C. Wemple, and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14:76-85.

Kinnell, P.I. 2005. Why the universal soil loss equation and the revised version of it do not predict event erosion well. Hydrological Processes 19: 851-854.

Litschert, S.E. 2009. Delta-Q and FOREST: Spatially explicit cumulative watershed effects models for forested watersheds. Ph.D. dissertation, Colorado State University, Fort Collins, CO.

Luce, C.H. and T.A. Black 1999. Sediment production from roads in western Oregon. Water Resources Research 35:2561-2570.

MacDonald, L.H. and D. Coe. 2007. Influence of headwater streams on downstream reaches in forested areas. Forest Science 53:148-168.

Megahan, W.F. and W.J. Kidd. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. Journal of Forestry 70:136-141.

Menning, K.M., D.C. Erman, K.N. Johnson, J. Sessions. 1997. Modeling aquatic and riparian systems, assessing cumulative watershed effects, and limiting watershed disturbance. In: Sierra Nevada Ecosystem Project: Final report to Congress, Addendum (2). Davis: University of California, Centers for Water and Wildland Resources.

Montgomery, D.R. 1994. Road surface drainage, channel initiation, and slope instability. Water Resources Research 30:1925-1932.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, K.W. King. 2002. Soil and Water Assessment Tool theoretical documentation. Temple, TX.

Ouyang, D., J. Bartholic, and J. Selegean. 2005. Assessing sediment loading from agricultural croplands in the great lakes basin. Journal of American Science 1(2): 14-21.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, 1997. Predicting soil erosion by water : a guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA ARS Agriculture Handbook 703, Washington, D.C.

Renwick, W.H., S.V. Smith, J.D. Bartley, and R.W. Buddemeier. 2005. The role of impoundments in the sediment budget of the conterminous United States. Geomorphology 71:99-111.

Semmens, D.J., and D.C. Goodrich, 2005. Planning Change: Case Studies Illustrating the Benefits of GIS and Land-Use Data in Environmental Planning. In: *Proceedings, International Conference on Hydrological Perspectives for Sustainable Development*, Roorkee, India, Feb. 23-25, 2005.

Semmens, D.J., W.G. Kepner, D.C. Goodrich, D.P Guertin, M. Hernandez, and S.N. Miller, 2006. From research to management: a suite of GIS-based watershed modeling, assessment and planning tools. In: *Proceedings, iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software". International Environmental Modelling and Software Society*, Voinov, A., Jakeman, A., Rizzoli, A. (eds). Burlington, USA, July 2006.

Sheridan, G.J. and P.J. Noske. 2007. A quantitative study of sediment delivery and stream pollution from different forest road types. Hydrological Processes 21:387-398.

Simon, A., W. Dickerson, A. Heins. 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States:transport conditions at the bankfull and effective discharge? Geomorphology 58: 243-262.

Ward, A. and S.W. Trimble. 2004. Environmental Hydrology. CRC-Lewis Press Boca Raton,Fl 475 pp.

Waters, T.F. 1995. *Sediment in Streams: Sources, Biological Effects and Control*. American Fisheries Society Monograph 7. 251 pp.

Wischmeier, W.H. and D.D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. Agriculture Handbook 282. USDA-ARS

Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall erosion losses: a guide to conservation planning. Agriculture Handbook 282. USDA-ARS

	FOREST	RUSLE	AGWA
Inputs	DEM Soils Climate	DEM Soils Climate NLCD	DEM Soils Climate NLCD Precipitation
Disturbances	Fire Logging Roads	NLCD	NLCD Roads*
Output	Catchment Road Erosion Production Riparian Road Erosion Production Hillslope Sed. Delivery Total Sed. Delivery	Erosion Production Sediment Delivery	Sediment Delivery

Appendix A: Basic differences in the inputs, disturbances modeled, and output of FOREST, RUSLE, and AGWA. * AGWA2 does not specifically account for road erosion production, except for roads that are large enough to appear as an NLCD class. Since road erosion production is the main source of anthropogenic sediment in forested watersheds, we overlaid the NLCD data with road data from the Topologically Integrated Geographic Encoding and Referencing (TIGER) dataset produced by the U.S. Census Bureau.