Assessing Cumulative Watershed Effects in the Central Sierra Nevada:
Hillslope Measurements and Catchment-scale Modeling

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Introduction

Cumulative effects result from the combined impact of multiple activities over space and time. Land and aquatic resource managers are particularly concerned with cumulative watershed effects (CWEs). CWEs can encompass a broad range of concerns, but the primary issues are the changes in runoff, water quality, channel morphology, and aquatic ecosystems at the watershed scale (Reid, 1993). Hence CWEs are a class of cumulative effects defined by multiple sources within a watershed and a common delivery mechanism (i.e., the drainage network) (Figure 1).

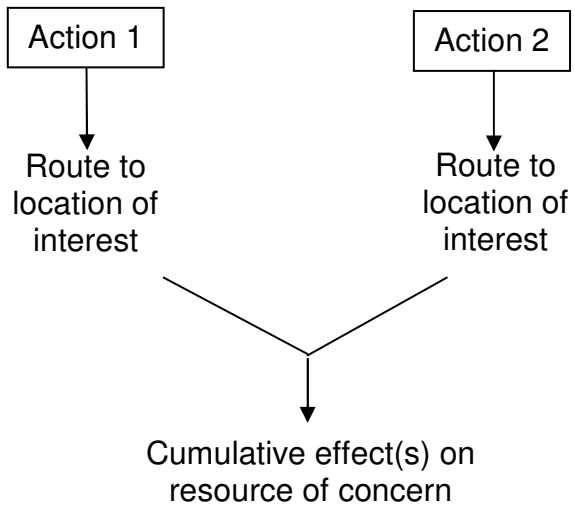

Figure 1. Multiple activities over space can lead to a cumulative watershed effect.

The assessment and prediction of CWEs has long been problematic (CEQ, 1997; MacDonald, 2000). Key steps in the assessment of CWEs include: (1) an evaluation of background conditions in the basin of interest; (2) collating and evaluating anthropogenic changes at the site scale; (3) routing the constituents of interest into the stream network; and (4) transmitting those products through the stream network and assessing their impact on the resources of concern.

The assessment of CWEs is further complicated by the need to consider the effects of time on the actions of concern. At the site scale there is a need to consider the recovery of different effects over time (e.g., hydrologic recovery or declining erosion rates with forest regrowth). Often there is a lag in the delivery of a given effect to a downstream location, and the persistence of a cumulative effect at a downstream location can be quite different from the persistence of the causal actions. The lags in delivery mean that the size of the basin of interest can directly affect the time scale of the analysis. The complexities of these different processes, when combined with the issues of temporal

and spatial scale, are largely why there is a lack of accepted procedures for assessing or predicting CWEs (Reid, 1993; CEQ, 1997; MacDonald, 2000).

The lack of procedures is surprising given the number of laws and regulations that require public agencies and private landowners to assess the potential cumulative effects of a proposed action. The National Environmental Policy Act (NEPA) requires federal agencies to assess the cumulative effect of any proposed action, and the California Environmental Quality Act (CEQA) has similar requirements for state agencies. The Clean Water Act and its amendments also may require the assessment of cumulative watershed effects. For example, the TMDL (Total Maximum Daily Load) process is effectively a cumulative effects assessment. The Endangered Species Act may require public agencies and private individuals to assess the effect of a proposed action on the habitat or population of threatened or endangered species. For aquatic organisms this effectively may require a watershed-scale assessment of the different factors affecting existing or potential habitat. Finally, the California Board of Forestry explicitly requires private landowners to consider cumulative watershed effects when submitting a Timber Harvest Plan.

Taken together, these laws force federal and private landowners to qualitatively or quantitatively assess existing and potential CWEs. At present the assessment of CWEs in the Sierra Nevada are severely limited by the lack of field data to quantify the effect of a given action, and tools to quantify and aggregate the effects of past, present, and proposed actions on the resources of concern at the watershed scale. The following sections summarize our recent efforts to: (1) quantify anthropogenic and natural sediment yields in forested areas in the Central Sierra Nevada; and (2) develop models for predicting changes in runoff and sediment production at the watershed scale.

Current Methods to Assess and Predict CWEs

There are a wide range of potential approaches to assessing CWEs (Figure 2), and these range from the qualitative checklist used by CDF to physically-based and spatially-explicit models such as DHSVM (Wigmosta et al., 1994). The most widely-used model is the Equivalent Roaded Area (ERA) procedure developed by the USDA Forest Service in the early 1980s. This is a lumped, conceptual model that quantifies the total disturbance in the watershed through the use of empirical coefficients and recovery curves for each activity (Cobourn, 1989). Two major limitations with this approach are: (1) it does not clearly indicate whether changes in flow or changes in sediment yields are being assessed; and (2) it is not spatially explicit (e.g., the effect of an activity does not vary with its location in the watershed).

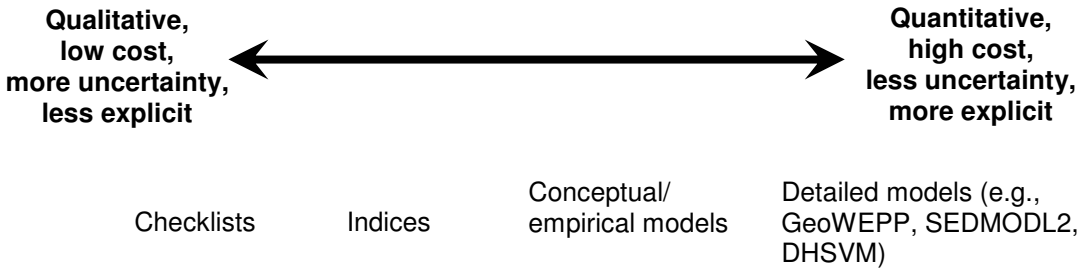

Figure 2. Continuum of approaches for assessing cumulative effects.

The development and use of more physically-based models to predict CWEs in the Sierra Nevada is severely hindered by the lack of primary data to predict site-scale changes in runoff and erosion. Our working presumption is that changes in sediment production due to forest management activities are of greater concern in the Sierra Nevada than the changes in flow induced by management. Studies from other areas have shown that roads and other anthropogenic disturbances can increase sediment production rates at the hillslope scale by one or more orders of magnitude relative to undisturbed conditions (Megahan and Kidd, 1972; Swanson et al., 1987; Weaver and Dale, 1978; Reid and Dunne, 1984). The increase in sediment production at the hillslope scale is likely to increase sediment delivery to streams, and this can adversely affect downstream aquatic ecosystems (Cederholm et al., 1981; Wemple et al., 1996; Nelson and Booth, 2002).

In contrast, timber harvest and roads on small research watersheds typically increase the size of peak flows by only 10-20% or a couple of cubic feet per second per square mile (Austin, 1999). Our preliminary assessment of stream channel conditions on the Eldorado National Forest suggests that increased sediment loads are a larger problem than channel degradation due to increases in the size of peak flows. Finally, it is extremely difficult to measure management-induced changes in discharge, while it is much more feasible to measure hillslope-scale changes in sediment production rates.

In fall 1999 we began measuring hillslope-scale sediment production rates as a first step towards the calibration and development of more spatially-explicit CWE models for use in the Sierra Nevada. The specific objectives were to: (1) quantify sediment production and sediment delivery from timber harvest, roads, wild and prescribed fires, off-road vehicles, and undisturbed areas; (2) quantify the year-to-year variability in sediment production; and (3) determine the effect of key site variables, such as elevation, slope, percent cover, soil type, and contributing area, on sediment production rates. Sediment production rates were measured by capturing sediment behind sediment fences, and then removing and weighing the captured sediment (Robichaud and Brown, 2002; www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm). Group comparisons were made using F-protected LSD.

In the first year we established 91 sediment fences. Our working hypothesis was that roads and severely burned areas would generate more sediment than other sources, so we installed 27 sediment fences at the outlets of road drainage structures (e.g., waterbars, rolling dips, and cross-relief culverts), 36 sediment fences at the outlets of waterbars on

skid trails, 7 sediment fences on rills and gullies draining off-road vehicle (ORV) trails, 15 sediment fences on hillslopes burned by prescribed fires, 3 fences on hillslopes burned by a high-severity wildfire, and 3 fences on minimally-disturbed hillslopes (Table 1).

Table 1. Number of sediment fences by landuse type for each of three wet seasons.

	Wet season		
Landuse type	1999-2000	2000-2001	2001-2002
Roads	27	47	66
Skid trails	36	48	10
OHV	7	7	7
Fire	18	18	3
Undisturbed	3	3	0
Totals	91	123	86

There was considerable variability in sediment production rates between the different land uses within the first wet season. The median sediment production rate from roads was 0.2 kg m^{-2}, or nearly an order of magnitude higher than any of the other sources (Figure 3). The sediment production rates within a given land use generally were highly skewed, with a few sites producing the majority of the sediment from that land use. Hence the mean sediment production rate from roads was 0.9 kg m^{-2}, or nearly five times the median value. In comparison, the mean sediment production rate was 0.1 kg m^{-2} from skid trails, 0.4 kg m^{-2} from ORV trails, and just 0.001 kg m^{-2} from minimally disturbed sites. When the burned sites were separated by burn severity, the sites burned at high severity had a mean sediment production rate of 1.1 kg m^{-2} (n=3), or approximately 1,000 times greater than the mean value of 0.001 kg m^{-2} from sites burned by prescribed fire (n=15).

Native surface roads produced 10-50 times more sediment than rocked roads. Skid trails on Holland soils produced an average of 0.9 kg m^{-2} of sediment (n=2), and this was significantly more than the mean value of 0.04 kg m^{-2} for the skid trails on all other soil types (n=34).

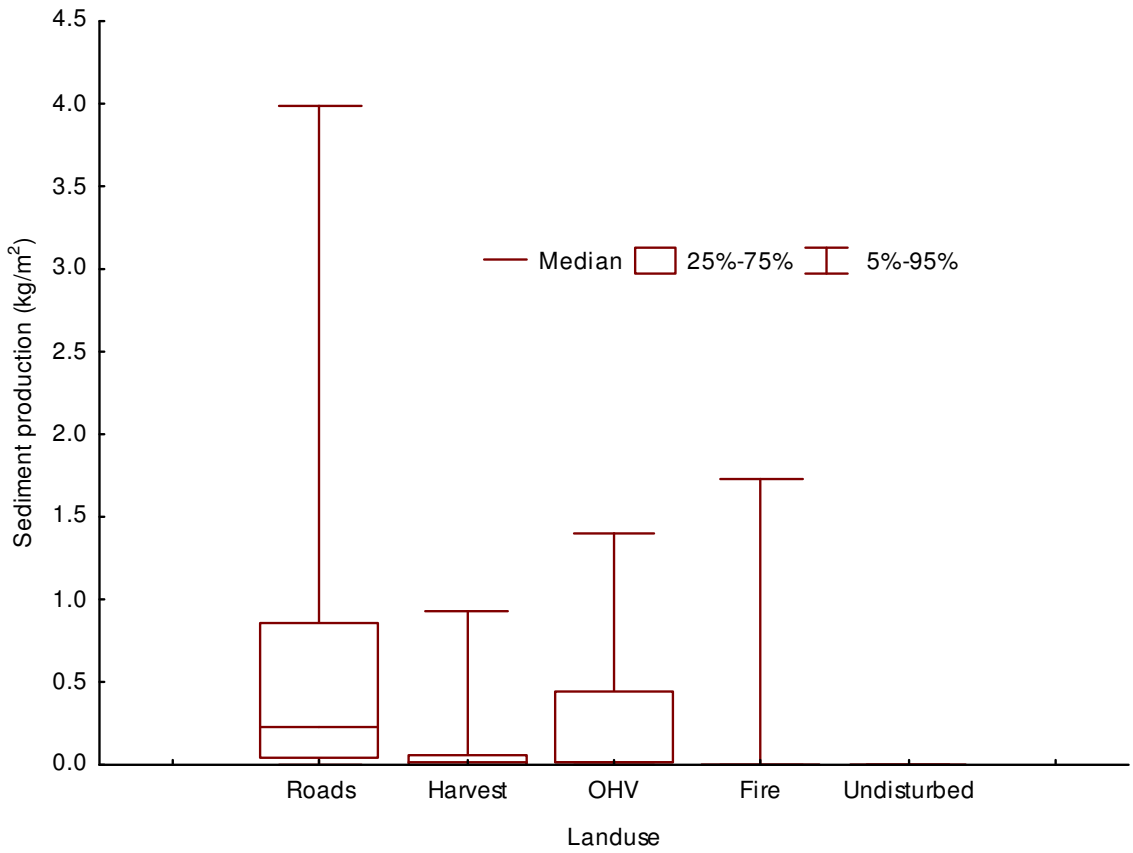

Figure 3. Sediment production by dominant land use for the 1999-2000 wet season.

The results from the first wet season supported our initial hypothesis and caused us to focus our efforts in the second and third years on sediment production from unpaved roads. Although we were not able to add any additional sediment fences on areas burned at high severity, the number of fences on roads increased from 27 in the first year to 47 in the second year and 66 in the third year (Table 1). Since some of the lower-producing sites were not monitored in all three years, we have a total of 300 fence-years of data.

Sediment production rates from roads in the second and third wet seasons were only 10-30% of the values measured in the first wet season (Figure 4). A similar decrease was observed for sediment production rates from skid trails, ORV trails, burned sites, and undisturbed areas. The largest decline was for the three sites burned at high severity, as the second year sediment production rates were an order of magnitude lower than in the first year, and the third year sediment production rates were another 70% lower than the values measured in the second year. This decrease is attributed primarily to the increase in vegetative cover, since percent cover has been shown to be the largest control on post-fire sediment production rates in other areas (e.g., Benavides-Solorio, 2003).

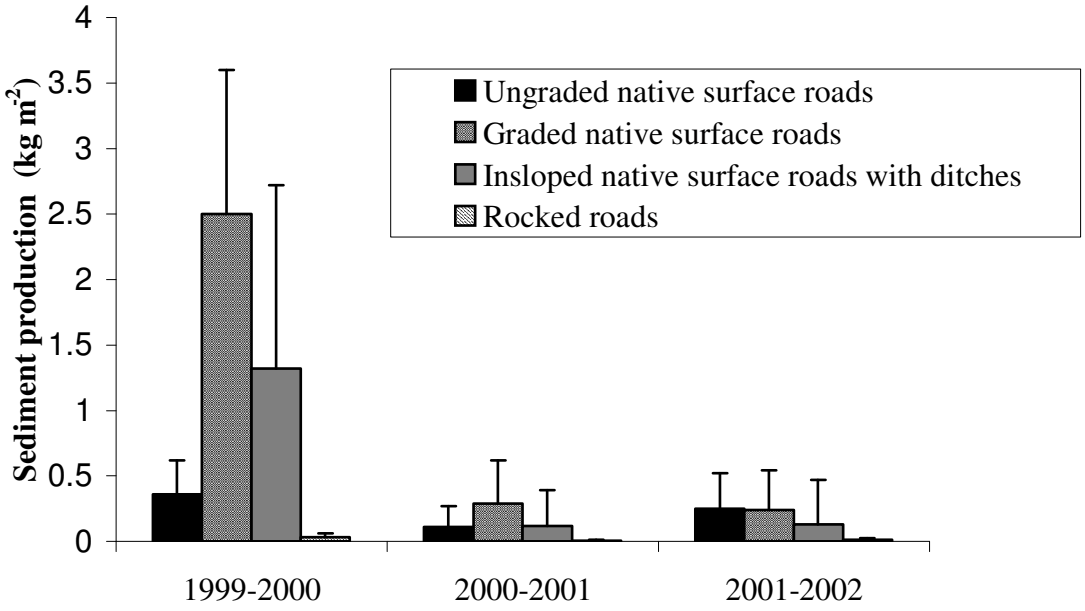

Figure 4. Magnitude and interannual variability in sediment production rates for various road drainage types and surfaces. Bars represent one standard deviation.

The decline in sediment production rates in the second and third seasons for the other land uses generally can be attributed to differences in the magnitude and type of precipitation. Total precipitation in the first wet season was very close to the long-term mean in the first wet season, but only 70% and 83% of normal in the second and third wet seasons, respectively. Perhaps more importantly, storms in the second and third wet seasons generally were colder than in the first wet season, so more of the precipitation fell as snow and precipitation rates were substantially lower. Hence the rainfall erosivity in the second and third wet seasons was only 440 MJ mm ha^{-1} hr^{-1}, or slightly more than half of the erosivity in the first wet season and only about 40% of the long-term mean. The larger and more persistent snowpack at most of our sites apparently protected the surface from rainsplash erosion and may also have slowed any overland flow.

Taken together, the three years of data confirm that roads, high-severity wildfires, ORV trails, and certain skid trails were the dominant sources of sediment at the hillslope scale. Sediment production rates were highly variable between sites within a year as well as between years. While the sample size for minimally-disturbed sites was small (n=3), none of these sites produced any sediment. Recent research indicates that long-term erosion rates are dominated by catastrophic but infrequent pulses of erosion triggered by wildfires and extreme storms (Kirchner et al., 2001). The implication is that natural erosion rates inbetween such events is very low, and this is consistent with our field observations.

Univariate analyses and stepwise multiple regression both indicated that road segment area times slope (A*S), annual erosivity (E_A), and road maintenance (recently-graded vs. ungraded) were significant controls on unpaved road erosion. An empirical model using these three variables explains 54% of the variability in annual road sediment

production. We also found that the native surface road segments receiving runoff from adjacent rock outcrops produced four times more sediment than comparable segments unaffected by rock outcrops. However, a dummy variable for the presence of rock outcrops was not significant in our multivariate analysis. The observed variations in sediment production rates between sites and between years show the difficulty of developing accurate predictive models for CWEs.

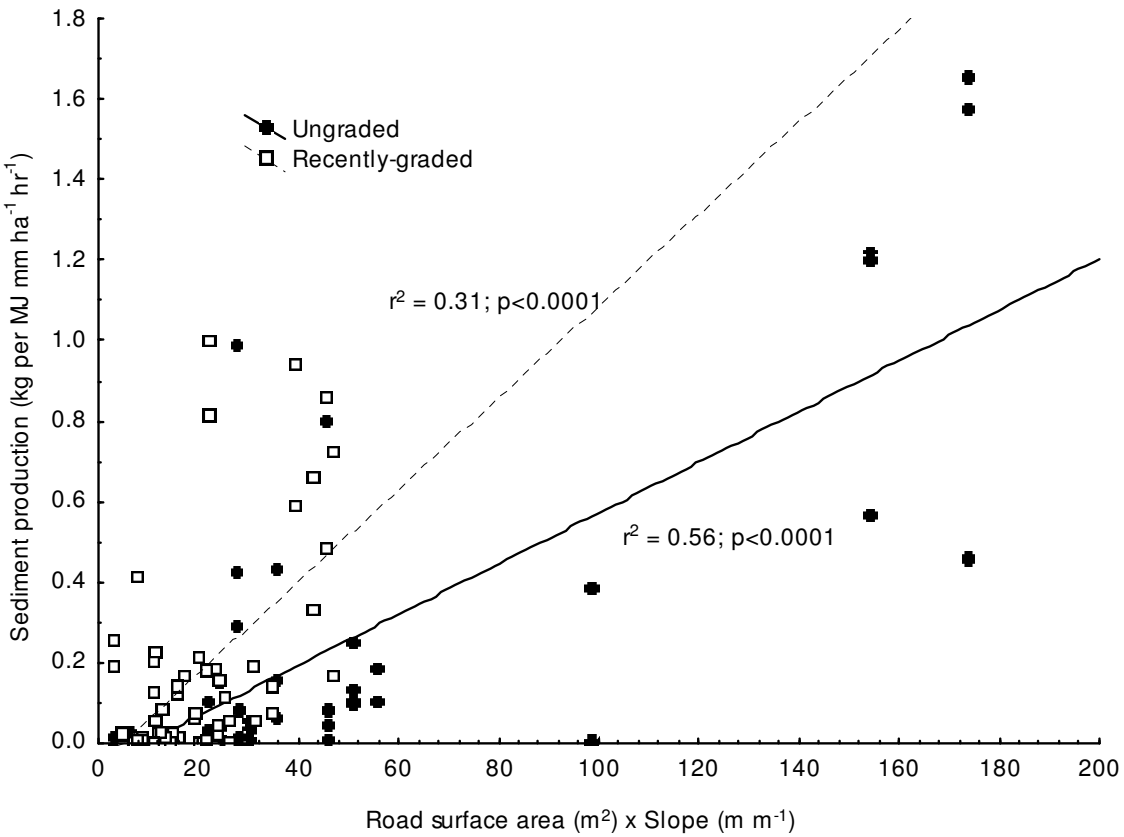

Figure 5. Sediment production vs the product of road surface area and road slope for recently-graded and ungraded native surface roads. Sediment production was normalized by annual erosivity. The regression lines for recently-graded and ungraded roads are significantly different (p=0.03).

Developing Models for Predicting CWEs

Our modeling goal is to develop flexible, user-friendly, GIS-based models to predict changes in flow, sediment production, and ultimately sediment delivery for watersheds ranging from approximately ten to several hundred square kilometers. As indicated by Figure 2, there is a wide range of potential models for assessing CWEs. Reid (1993) noted that simpler models are widely used but can't represent the underlying processes and are largely unverified, while more physically-based, spatially-explict models should be more accurate but are rarely used.

We are attempting to take a middle road. Our first objective was to explicitly separate the procedures used to assess changes in flow from changes in sediment production. Second, we wanted to utilize the capability of spatially-explicit models,

while still recognizing the basic data limitations and desire for models that could be easily applied by a range of users. Third, we wanted to provide users with the flexibility to change values and recovery rates to better represent their local conditions. The ability to readily change coefficients and rates of recovery facilitates an assessment of model sensitivity to the selected values, and this is an important tool given the uncertainty in predicting the effect of a given disturbance on different sites. Finally, we wanted to take a modular approach so that new procedures could be added as these are developed or different issues arise.

The first model, DELTA-Q version 1.0, calculates changes in runoff based on activities such as forest harvest and fires (see modeling link at http://www.cnr.colostate.edu/frws/people/faculty/macdonald/macdonald.html). This calculates catchment-scale changes in high, median, and low flows resulting from changes in forest cover due to timber harvest or fires. Changes can be calculated in absolute terms or as a percentage. The input data are GIS layers representing the extent, type, and years of the different activities. Users determine the flows of interest and select values for the change in flow for each activity type and the time to hydrologic recovery. Help files list the calculated changes in flow for different flow percentiles from 26 paired-watershed studies (Austin 1999). Each model run calculates the change in flow over the chosen time period for one activity layer (e.g., forest harvest or fires). The model sums the changes in flow from multiple runs using different activity layers to determine the total change in flow for the area of interest. Tables of the individual and total changes in flow over time can be exported as text files for plotting, report preparation, or further analysis.

The second model is the FORest Erosion Simulation Tool (FOREST). This is designed to calculate the changes in surface erosion resulting from forest harvest, unpaved roads, and fires. The explicit separation of changes in flow and surface erosion should help users recognize the differences in the magnitude of change and length of the recovery period for these two different types of CWE. Once FOREST is released in late 2003, we will begin working on a third model to route the calculated sediment production rates into and through the stream network.

As in the case of DELTA-Q, the input data for FOREST are one or more ArcInfo coverages with the activities of interest. There are separate procedures for calculating sediment production from linear features (e.g., roads) and from polygons. The modular structure means that FOREST provides the user with several options for calculating sediment production rates, depending on data availability and the desired level of complexity.

For roads and other linear features, the options within FOREST include fixed sediment production rates per unit road length for each road type and empirical models (e.g., Luce and Black, 1999). Alternatively, the user can run a set of simulations outside of FOREST using models such as WEPP:Road (http://forest.moscowfsl.wsu.edu/fswepp/). Depending on the data available and the desired level of complexity, the user can stratify their roads layer and then use FOREST to assign spatially-explicit values to the different road segments. A lookup table of published road erosion values is provided to help users determine values for their sites.

The polygon module calculates sediment production rates from activities such as forest harvest or fires. The required input is one or more polygon coverages that include

the type(s) of disturbance and year of each activity. Users assign a first-year sediment production rates to each activity and the time needed for erosion rates to return to background levels. At this stage a linear recovery is assumed, although users can also specify no recovery, as might be the case for continuously-used unpaved roads. An additional polygon coverage can be used to adjust sediment production rates for factors such as fire severity, soil type, or elevation.

To help users assign sediment production rates, FOREST provides a lookup table of published post-fire erosion rates. Alternatively, the user can use programs such Disturbed WEPP to calculate sediment production rates and bring these in to FOREST. In contrast to DELTA-Q, FOREST converts vector data to rasters to perform raster-based calculations. Model outputs include sediment production grids for each year as well as a summary table of sediment production rates over time for the areas of interest. When FOREST is run on multiple layers of overlapping activities, the results can be combined into a grid to show maximum sediment production rates for the time period of interest.

The raster-based approach of FOREST will facilitate the development of modules to deliver the sediment into and through the stream network. Given the data limitations and uncertainties in predicting sediment transport, we expect that the sediment delivery models modules will use a combination of empirical data and relatively simple algorithms based on key variables such as slope and drainage area. The final step will be to test the validity of these CWE models against data from a range of managed and relatively unmanaged watersheds. We also are expanding the scope of our field studies to sites in the southern Sierra and in the southern Cascades.

Conclusions

Cumulative watershed effects are an important concern of resource managers, and the assessment of CWEs is required by both state and federal laws. There is a need for improved models to more explicitly assess the changes in flow and changes in sediment production for forested watersheds in the Sierra Nevada. Current methods are hampered by both the lack of accurate input data based upon field measurements and the absence of spatially-explicit, user-friendly models.

Our field studies have focussed on measuring sediment production rates in forested areas in the Central Sierra. In general, unpaved roads and areas burned at high severity have the highest sediment production rates. Within our study area sediment production rates from roads can be predicted from road surface area times slope, rainfall erosivity, type of road surface (rocked or native surface), and whether it has been recently graded. Sediment production rates from severely-burned areas declined rapidly over time, although this decline was confounded by the lower rainfall erosivity in the second and third wet seasons. Sediment production rates varied considerably between sites and between years, and this illustrates the difficulty of assessing CWEs.

The DELTA-Q model has been developed to calculate changes in flow from fires and forest management activities, and we are finalizing a separate model to calculate changes in surface erosion. A third model is proposed to route sediment into and through the stream network. Continuing field studies will provide additional data on sediment production rates and the delivery of this material to the stream channel. Once the various models are operational, the predicted changes in runoff and sediment yields at the watershed scale need to be tested against measured values and compared to aquatic

resource conditions for forested watersheds with a varying levels of natural and anthropogenic disturbance.

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