Assessing Cumulative Watershed Effects in the Central Sierra Nevada: Hillslope Measurements and Catchment-Scale Modeling[1]

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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 primary issues are changes in runoff, water quality, channel morphology, and aquatic ecosystems at the watershed scale (Reid 1993). CWEs are a class of cumulative effects defined by multiple sources within a watershed that share a common delivery mechanism, the drainage network *(fig. 1)*.

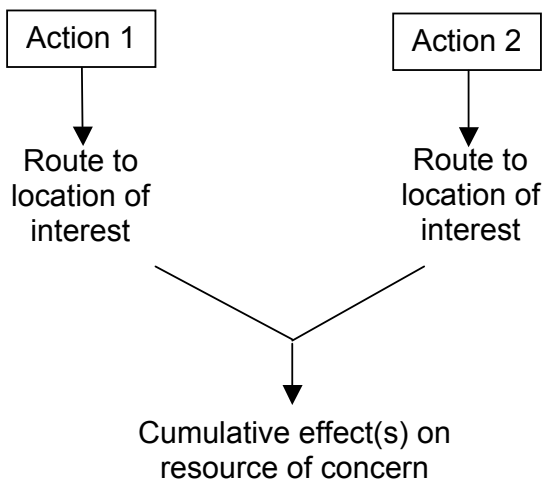

Figure 1— Multiple activities over space can lead to a cumulative watershed effect.

The assessment and prediction of CWEs has long been problematic (CEQ 1997, MacDonald 2000). Key steps in the assessment of CWEs include: (1) evaluating 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.

Assessment of CWEs is further complicated by the need to consider effects of time on actions of concern. At the site scale, there is a need to consider the recovery of different effects over time (for example, 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

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the persistence of the causal actions. 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 manifestations of these processes over time and space, largely explain the reason for a lack of accepted procedures for assessing or predicting CWEs (CEQ 1997, MacDonald 2000, Reid 1993).

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 proposed actions, 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 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, assessments 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 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 Cumulative Watershed Effects

There are a wide range of potential approaches to assessing CWEs *(fig. 2),* ranging from the qualitative checklist used by the California Department of Forestry (CDF) to physically based and spatially explicit models, such as DHSVM (Wigmosta and others 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 total disturbance in the watershed through the use of empirical coefficients and recovery curves for each activity (Cobourn 1989). This approach has two major limitations: (1) it does not

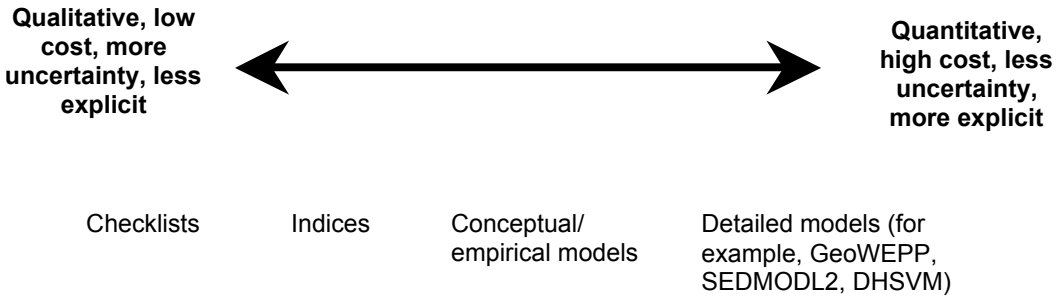

Figure 2— Continuum of approaches for assessing cumulative effects.

clearly indicate whether changes in flow or changes in sediment yields are being assessed and (2) it is not spatially explicit (in other words, the effect of an activity does not vary with its location in the watershed).

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

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

In fall 1999, hillslope-scale sediment production rates were measured as a first step toward the calibration and development of more spatially explicit CWE models for use in the Sierra Nevada. 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 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, 91 sediment fences were established. The working hypothesis was that roads and severely burned areas would generate more sediment than other sources, so 27 sediment fences were installed at the outlets of road drainage structures (such as 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 land use type for each of three wet seasons.*

	Wet season		
Land use type	**1999-2000**	**2000-2001**	**2001-2002**
Roads	27	47	66
Skid trails	36	48	10
Off-road vehicle	7	7	7
Fire	18	18	3
Undisturbed	3	3	0
Totals	91	123	86

Considerable variability in sediment production rates was evident 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 *(fig. 3)*. In general, sediment production rates for a given land use 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 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 to 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), which was significantly more than the mean value of 0.04 kg m^{-2} for the skid trails on all other soil types (n = 34).

Results from the first wet season supported the initial hypothesis and caused a focusing of efforts in the second and third years on sediment production from unpaved roads. Although additional sediment fences were not placed in areas burned by high-severity fire, 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)*. Because some of the lower-producing sites were not monitored for all 3 years, the study includes a total of 300 fence-years of data.

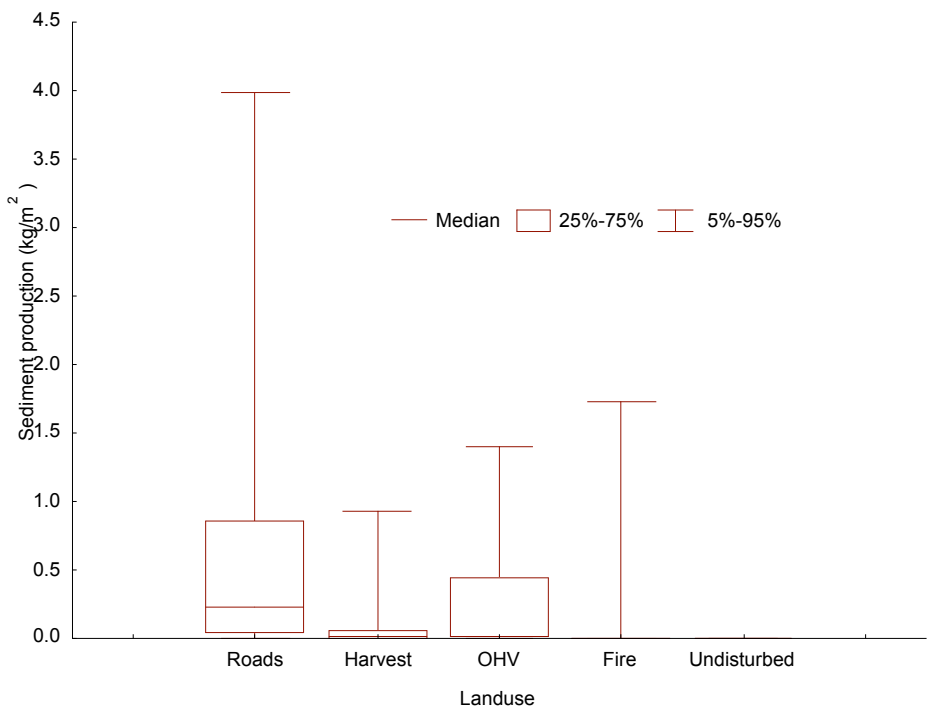

Figure 3— Sediment production by dominant land use for the 1999–2000 wet season.

Sediment production rates from roads in the second and third wet seasons were only 10 to 30 percent of the values measured in the first wet season *(fig. 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 percent lower than the

values measured in the second year. This decrease is attributed primarily to the increase in vegetative cover, because percent cover has been shown to be the largest control on post-fire sediment production rates in other areas (for example, Benavides-Solorio 2003).

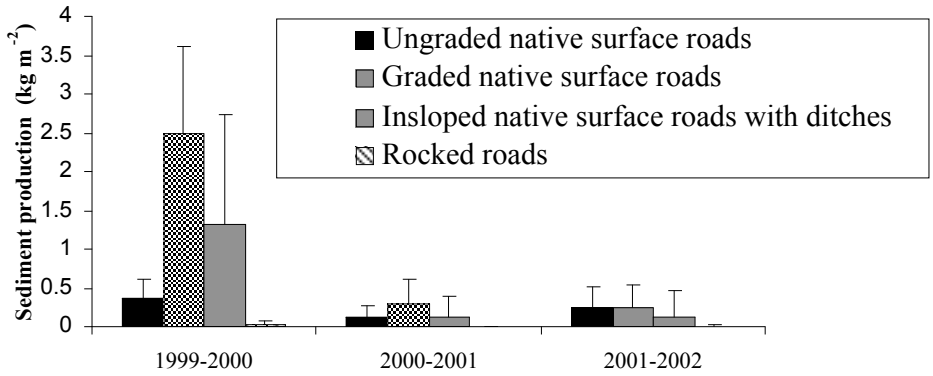

Figure 4— Magnitude and interannual variability in sediment production rates for various road drainage types and surfaces. Bars represent one standard deviation.

Declines in sediment production rates in the second and third seasons for the other land uses can be generally attributed to differences in magnitude and type of precipitation. Total precipitation in the first wet season was very close to the long-term mean but only 70 percent and 83 percent 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. Hence, 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 percent of the long-term mean. The larger and more persistent snowpack at most of the sediment fence sites apparently protected surfaces from rain splash erosion and may also have slowed overland flow.

Taken together, the 3 years of data confirmed 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. Although 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 and others 2001). The implication is that natural erosion rates between such events are very low, and this is consistent with the authors' field observations.

Univariate analyses and stepwise multiple regression both indicated that road segment area times slope (A*S), annual erosivity (EA), and road maintenance (recently graded versus ungraded) were significant controls on unpaved road erosion. An empirical model using these three variables explains 54 percent of the variability in annual road sediment production *(fig. 5)*. Study results also showed that 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 the multivariate analysis. The observed variations in sediment production rates between sites and between years illustrate the difficulty of developing accurate predictive models for CWEs.

Developing Models for Predicting Cumulative Watershed Effects

The authors' goal for modeling is to develop flexible, user-friendly, geographic information systems (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,* a wide range of potential models exists for assessing CWEs. Reid (1993) noted that simpler models are widely used but are incapable of representing underlying processes and are largely unverified, whereas more physically based, spatially explicit models should be more accurate but are rarely used.

The authors of this paper have attempted to take a middle road. One objective was to explicitly separate the procedures used to assess changes in flow from those used to assess changes in sediment production. Another objective was to use the capability of spatially explicit models, while recognizing basic data limitations and the desire for models that could

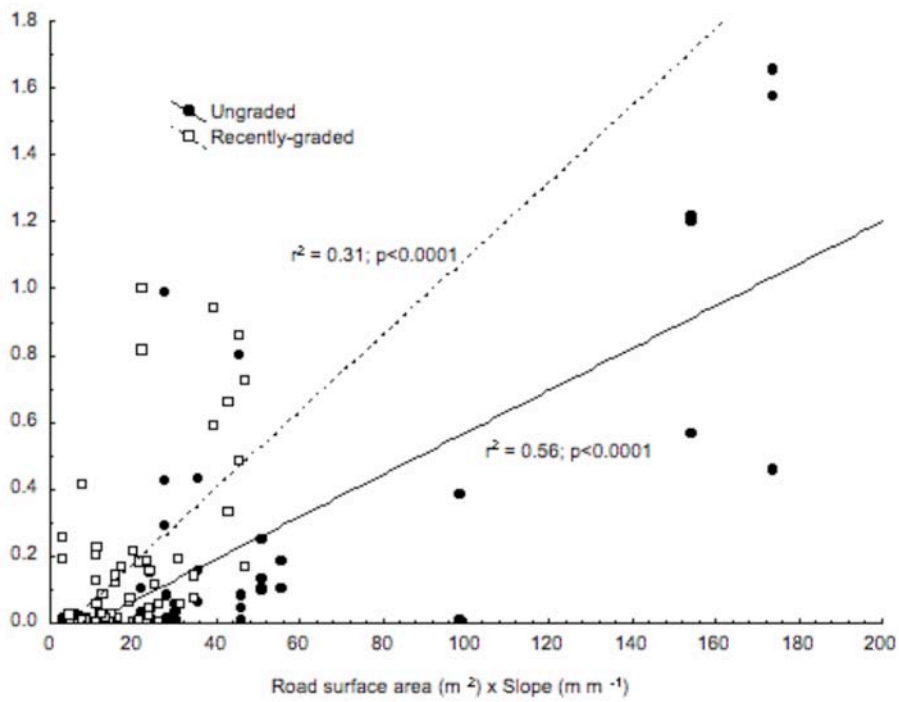

Figure 5— Sediment production versus the product of road surface area and road slope for recently graded and ungraded native surface roads. Sediment production was normalized by annual erosivity. The regression lines for recently graded and ungraded roads are significantly different (p = 0.03).

be easily applied by a range of users. The third objective was to provide users with the flexibility to change values and recovery rates to better represent local conditions. The ability to readily change coefficients and rates of recovery facilitates an assessment of model sensitivity to the selected values; this is an important tool given the uncertainty in predicting the effect of a given disturbance on different sites. Finally, a modular approach was used so that new procedures could be added as they are developed or different issues arise.

The first model, DELTA-Q version 1.0, calculates changes in runoff on the basis of 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 (for example, forest harvest or fire). 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 model is designed to calculate 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 differences in the magnitude of change and length of the recovery period for these two different types of CWE. Once FOREST is released, the authors 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 (such as roads) and 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 (for example, 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 available data and desired level of complexity, users can stratify their roads layer and then use FOREST to assign spatially explicit values to 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 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, programs such as Disturbed WEPP can be used to calculate sediment production rates, which can then be brought into 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 development of modules to deliver the sediment into and through the stream network. Given the data limitations and uncertainties in predicting sediment transport, it is expected that the sediment delivery model's 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.

The authors are expanding the scope of their field studies to sites in the southern Sierra Nevada and southern Cascades.

Conclusions

Cumulative watershed effects are an important concern of resource managers, and both state and Federal laws require assessment of CWEs. There is a need for improved models to more explicitly assess changes in flow and 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.

The field studies described here have focused on measuring sediment production rates in forested areas in the central Sierra Nevada. In general, unpaved roads and areas burned at high severity have the highest sediment production rates. Within the study area, sediment production rates from roads can be predicted on the basis of road surface area times slope, rainfall erosivity, type of road surface (rocked or native surface), and whether the road has been recently graded. Sediment production rates from severely burned areas declined rapidly over time although this decline was confounded by 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 resulting from fires and forest management activities, and a separate model to calculate changes in surface erosion is being finalized. 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 delivery of this material to the stream channel. Once the various models are operational, 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 varying levels of natural and anthropogenic disturbance.

Acknowledgments

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