Sediment Production on Forest Road Surfaces in California's Redwood Region: Results for Hydrologic Year 2005-2006

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Abstract: This paper describes results of the first year (hydrologic year 2005-2006) of a study of surface erosion on forest roads on the Jackson Demonstration State Forest, Mendocino County, California. Estimated annual sediment production varied greatly among sites, from 0.05 $kg/m^2/yr$ to more than 4 $kg/m^2/yr$. The estimated share of suspended sediment in total sediment production ranged from 33% to 86%. In this paper, we describe the study method, present basic results, and discuss practical issues in data collection and interpretation.

Keywords: Forest roads, surface erosion, sediment production

Introduction

This paper describes instrument and study design, data collection, and preliminary results from a pilot study of surface erosion associated with forest roads on the Jackson Demonstration State Forest in California's coast redwood region. The study is a joint effort by the California Department of Forestry and Fire Protection and NOAA Fisheries. Our goals were to test the technology and to collect data over a representative range of conditions. These data are useful in that they were previously unavailable for the redwood region and because they provide a basis for assessing the predictive power of erosion simulation models.

Annual sediment production for hydrologic year 2005-2006 varied significantly across road segments, from much less than 1 $kg/m^2/yr$ to more than 4 $kg/m^2/yr$. Rocked segments produced much less sediment than most unsurfaced segments, though two unsurfaced segments produced amounts comparable to the rocked segments. The estimated share of suspended solids in total sediment production ranged from 33% to 86%, with no clear relation to road characteristics. Annual rainfall measured in the Caspar Creek Watershed, where four of the ten sites are located, was 147% of normal, the third wettest year since 1962. A more definitive assessment of sediment production on our study sites will emerge as we develop a time series of data in subsequent years and overcome some of the technical difficulties encountered in this first year of the study, as described below.

Methods

Study Area and Site Characteristics

The ten road segments in this road surface erosion study are located on the Jackson Demonstration State Forest in western Mendocino County, California. The study area has a Mediterranean climate, with most of the precipitation occurring during the months of November through April. The area is mountainous, with elevations ranging from sea level to 880 meters (2,850 feet) in the east. Topography is generally steep and dissected as a result of rapid uplift rates. Underlying geologic materials are dominated by coastal belt Franciscan sandstone, and soils range from gravelly loam to fine-grained with a high clay content.

Study sites were chosen to represent a range of grade, surface, and traffic conditions typical of forest roads in the redwood region. Site selection was also influenced by operational considerations such as placement on the hillslope, travel distances, and reducing the risk of vandalism. Road segments were generally crowned with an inside ditch. Individual site conditions varied in topography, cut-bank height, ditch vegetation, and overhead canopy. Road surface conditions were also variable. Some unsurfaced roads contained a fraction of native rock, while rocked roads had variations in the condition of applied rock. Sporadic surface flow was present from cut banks at four sites and varied with storm intensity. The road segments selected are representative of many roads on the forest and in the region, but differ from contemporary new construction standards that require outsloping and rolling dips to reduce concentration of runoff. Basic information on the ten study sites is presented in Table 1.

Surface runoff on each road segment is directed to an inside ditch, from which a culvert directs it to devices that measure runoff and sediment production, as described below. Thus, the inside ditch is part of the road segment profile, although its relative contribution to sediment production on the road segment is unknown. The catchment area for runoff on each site was estimated from the base of the cut bank to the crown in the road that serves as a "water divide." Because the actual catchment area for each segment cannot be known precisely, and will likely vary to some extent with rainfall intensity, we are exploring the sensitivity of our results to potential measurement error. However, in this paper we report results based on the single catchment area value deemed most probable for each segment.

Instrument Design and Calibration

Our method of estimating runoff and sediment production is based on a design by Black and Luce (2007). Each site has a settling basin that captures coarse sediment generated on the road segment, a tipping bucket with event logger that enables estimation of total runoff, and a splash device that collects a subsample of the runoff for analysis of suspended solids. A 5 ml subsample (c. 0.05% of tipping volume) is collected at each tip of the approximately 10-liter bucket and flows through a flexible tube into a closed 19-liter (5-gallon) bucket, which acts as a reservoir for composite post-storm sampling.

Fig. 1: The settling basin and tipping bucket during initial calibration. The settling basin, made of 122 cm (48") diameter corrugated metal pipe, catches runoff from the road segment, allowing coarse sediment to settle. The runoff then passes through a rectangular arm and into the tipping bucket, shown here just after having tipped to the right. A subsample intake opening, obscured by the water in this photo, catches a 5-ml flow sample, which is routed to a bucket from which a composite sample is later collected for laboratory analysis of suspended solids.

Each tipping bucket is calibrated by providing flow at a known rate, using a flow meter, and recording the resulting duration between tips. Repeating this procedure with different flow rates enables estimation of a calibration curve relating flow rate to duration between tips, as shown in Figure 2. Durations recorded by the data logger can then be used in conjunction with the calibration curves to estimate runoff on each segment, generating a fine-scale hydrograph for each segment throughout the winter season.

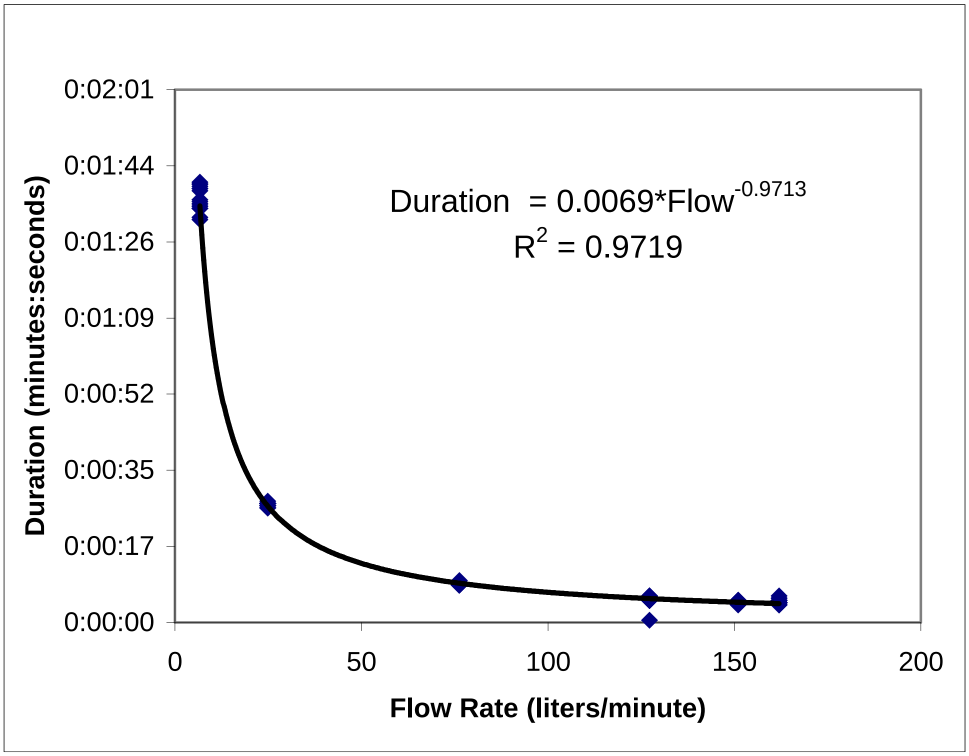

Fig. 2: Pre-season calibration curve for site 10. Fitting a power curve to tipping time data at known flow rates provides a relation between tipping times, downloaded from the data logger, and flow rates. After this relation is inverted to express flow as a function of duration, it is used in equation 1 below to estimate total runoff.

Data Collection and Analysis

Runoff and suspended solids data were collected throughout the rainy season. Regular visits, sometimes several per week, to the study sites were necessary to download tipping times from the event loggers. When the 19-liter buckets containing splash samples appeared to be nearing capacity, or when a sample had not been taken for several weeks, a mechanically agitated composite sample was collected from the buckets for analysis of suspended solids at a commercial laboratory using the EPA 160.2 protocol. The buckets were then cleaned and emptied. We measured total suspended solids (TSS) rather than suspended sediment concentration (SSC) due to budget considerations and the finding in Gray *et al.* (2000) that these measures differ little when the proportion of coarse sediment is small. In our study, the settling basin captured most of the coarse sediment before TSS samples were taken, minimizing the likely divergence between TSS and SSC.

To estimate runoff on each segment *i* during an interval *j* between consecutive tips of the tipping bucket, the flow rate associated with interval *j*'s duration (derived from the calibration curve) is multiplied by that duration. That is,

$$1) \quad RUNOFF_{ij} = DURATION_{ij} * FLOW_{ij} = DURATION_{ij} * (DURATION_{ij}^{1/\beta_{ij}})/\alpha_{ij}$$

where $RUNOFF_{ij}$ is the runoff volume from site *i* during interval *j*, $DURATION_{ij}$ is the time elapsed during interval *j*, $FLOW_{ij}$ is the runoff rate derived from the calibration curve for intervals of *j*'s duration, and α_{ij} and β_{ij} are the calibration coefficients for instrument *i* in interval *j* (in the example given in Figure 2, these are 0.0069 and –0.9713, respectively). Note that the calibration coefficients are time-varying, due to interpolation between pre- and post-season calibration values, a point we address in the discussion.

Letting *k* be an index of the period between two consecutive samples of total suspended solids, production on site *i* for the period *k* was estimated as the product of estimated runoff (L) and the associated TSS concentration (mg/L):

$$2) \quad TSS_{ik} = SAMPLE_{ik} * RUNOFF_{ik} = SAMPLE_{ik} * \sum_{j \in k} RUNOFF_{ij}$$

Note that $RUNOFF_{ik}$ is calculated as the sum of runoff over the between-tip intervals *j*, of which there are generally thousands per interval *k* between successive TSS samples. Thus, this measure of TSS_{ik} assumes the estimated TSS concentration $SAMPLE_{ik}$ applies to all runoff during period *k*. The results reported below reflect this assumption, as we have not yet tested the sensitivity of our results to other possibilities (e.g., interpolation between consecutive estimates of TSS, since discrete sampling of TSS leads to estimates that may take large steps from interval to interval, whereas they are almost certainly varying more smoothly over time).

Finally, annual values for runoff and TSS on site *i* are simply the sums of periodic values over *j* and *k*, respectively.

The coarse sediment captured by each settling basin was weighed at the end of the winter season with a 2,000 kg (+/- 500g) electronic dynamometer/crane scale. Each settling basin was topped off with water and the tank containing sediment and water was weighed and compared to previous weights of the tank and water without sediment. Several tanks filled mid-season, requiring weighing by hand due to restricted winter access on unsurfaced roads. The tanks were emptied by hand into 19-liter buckets that were transferred to a 38-liter (10-gal) bucket prior to weighing with the 2,000 kg crane scale mounted on a surveying tripod. The transfer to the 38-liter bucket was intended to minimize the number of measurements and effects of scale error. The mass estimates of the tank with the sediment-water mixture and with water alone were used to estimate the mass of dry sediment as in Black and Luce (2007):

3) $$M_S = \frac{\rho_S (M_{TSW} - M_{TW})}{\rho_S - \rho_W}$$

where M_S is the dry mass of sediment, M_{TSW} the mass of the tank with sediment and water, M_{TW} the mass of the tank filled with water alone, ρ_S is the particle density of sediment, and ρ_W is the density of water. We assume a sediment particle density of 2750 kg/ m^3 (see Wosika 1981, Appendix B) and a water density of 1000 kg/m^3.

Results

Table 1 shows summary results from the first year and information on characteristics of the ten road segments in the study. Figure 3 presents the same sediment information in a different form to allow easier comparison. The limited number of replications and variety of topographic conditions do not support a meaningful statistical analysis of the relation between sediment production and segment characteristics. Nevertheless, these results suggest that the rocked roads in this study produce less sediment than the native-surface roads, as expected. The proportions of coarse and suspended sediments vary considerably among sites, but not in any obvious relation to road characteristics: there are both rocked and unrocked roads that produce high relative proportions of both fine and coarse sediment.

Table 1. Site Characteristics and Summary Results for HY2005-2006. Winter traffic was not measured because it was limited to occasional light-duty vehicles. The final column is the ratio of suspended sediment to total sediment.

	Surface	Winter Traffic	Ditch (percent vegetated)	Grade	Area (m2)	Total Sediment (kg/m2)	Suspended Sediment Share
Site 1 (Rd 1000-1)	Unrocked	Light	10%	6%	1031	3.76	59%
Site 2 (Rd 240-1a)	Unrocked	None	0%	4%	716	4.15	41%
Site 3 (Rd 90-1)	Unrocked	None	10%	6%	634	1.34	73%
Site 4 (Rd 210-2)	Unrocked	None	10%	6%	778	0.07	49%
Site 5 (Rd 210-1)	Unrocked	None	10%	7%	560	0.12	33%
Site 6 (Rd 240-1)	Unrocked	None	0%	9%	399	4.57	54%
Site 7 (Rd 600-4)	Rocked	Light	75%	4%	757	0.05	35%
Site 8 (Rd 620-4)	Rocked	Light	30%	7%	452	0.23	86%
Site 9 (Rd 640-7)	Rocked	Light	30%	7%	723	0.10	58%
Site 10 (Rd 640-1)	Rocked	Light	20%	4%	573	0.23	40%

Using an assumed road surface bulk density of 1,600 kg/m^3 (Coe 2006), the sediment production rates given in Figure 3 correspond to surface depth loss rates of 0.03 mm/yr to 2.85 mm/yr.

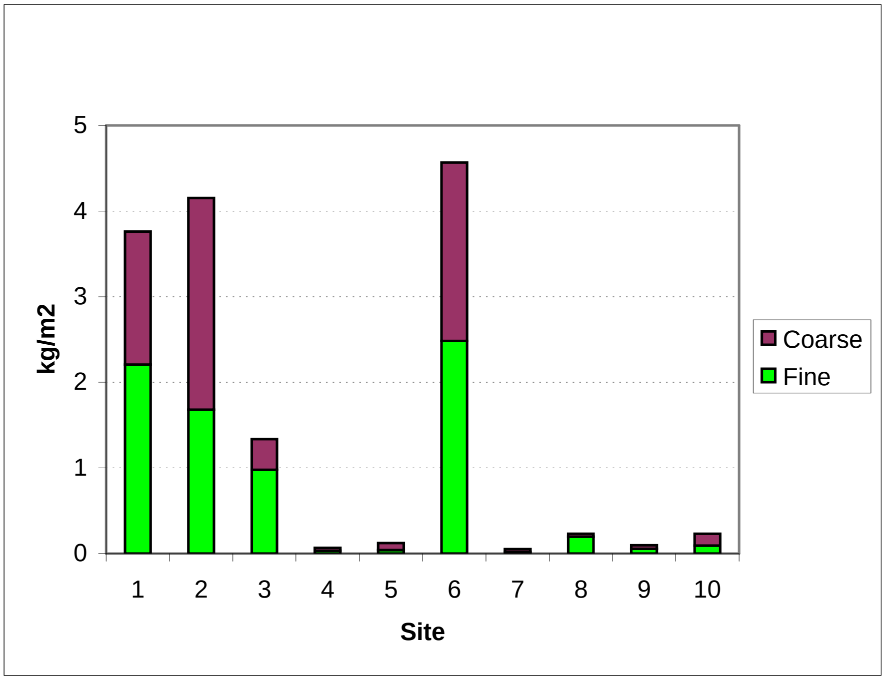

Fig. 3: Coarse and Fine Sediment Production, HY2005-2006. Data are normalized by area. Sites 1-6 are unsurfaced while sites 7–10 are rocked. While the highest-producing road segments were all unsurfaced, two unsurfaced segments (4 and 5) produced less sediment than the higher-producing rocked segments (8 and 10).

Discussion

Study results to date indicate that both total sediment production rates and the share of suspended sediment in total sediment differ greatly among sites. All four of the highest-producing segments in our study are unsurfaced, but two unsurfaced segments (4 and 5) produced less sediment than at least two rocked segments (8 and 10). Some of this variation can be attributed to known site variability, e.g., site 2 was the only one graded in the summer of 2005. Other factors, such as geology and ditch function, no doubt played a role as well, but we did not have sufficient data to support a statistical analysis of factors influencing variability in sediment production. Two points are particularly worth noting in interpreting our results. First, HY2005-2006 was a particularly wet year, with the North Fork of Caspar Creek reaching its highest peak flow since 1974. Second, we have not attempted to control for the influence of traffic, since all our road segments are either closed in winter or are believed to be used by 10 or fewer light-duty vehicles (pickups and sedans) per week.

Our results were generally consistent with other recent studies. An application of the WEPP simulation model (Ish and Tomberlin 2007) generated a mean long-term surface erosion rate estimate of 4.14 kg/m^2 on native surface roads in our study area, which is similar to the higher sediment production rates shown in Fig. 3. In studies from the interior portions of California, Coe (2006) reported a 16-fold difference in median sediment production rates between rocked and un-rocked road segments in the central

Sierra Nevada, while Korte and MacDonald (2007) found that native and mixed surface roads produced approximately three times the sediment as gravel surfaced roads in the southern Sierra Nevada.

The results presented here are preliminary, as they represent data from a single year with unusually heavy precipitation, and we have not yet explored the sensitivity of the results to uncertainties about sediment concentrations, catchment areas, and equipment function. A particularly important example of the latter was marked differences in the calibration coefficients for some tanks before and after the rainy season. Because we cannot know the rate at which the calibration coefficients changed during the season, the results reported here are based on a simple linear interpolation over time between the pre- and post-season calibration coefficients. Examining the sensitivity of our results to other possible patterns of change in the calibration coefficients—for example, such that the initial coefficients were operative until the last day of the season, or that the final coefficients were operative after the first day of the season—will enable us to bound the range of results consistent with our pre- and post-season calibration measures.

Additionally, several known technical problems add to the uncertainty in these HY2005-2006 results. Because it was a heavy rain year and the data loggers could only record 8150 tips, 47 of 338 total data downloads (14%) indicated that the data logger had filled, resulting in some lost data. There was also some minor equipment damage due to site visitors, e.g., on two occasions the tubing directing runoff subsamples to a collection reservoirs was removed. On site 7, an old buried culvert was found to be directing a significant amount of water from the study segment under the road and away from our instruments.

There are important questions related to road surface runoff and erosion that are beyond the scope of our study. We have not attempted to develop a statistical analysis of the factors contributing to road sediment production, to assess delivery of sediment to the stream network, nor to investigate the share of organic material in sediment production (although we have begun to examine the organic/inorganic breakdown in the second season of data collection).

The goals of this study are more limited: 1) to examine the feasibility of a particular approach to estimating road surface erosion in the redwood region, and 2) to generate estimates of sediment production on a representative range of road segments. The results presented here suggest that the method generates useful information, though at a significant cost: instrumentation at each site cost approximately $1800, while project initiation and data collection during the first year required approximately one staff person-year.

Literature Cited

Black, Thomas A., and Charles H. Luce. 2007 (8/15/2007 version). Measuring Water and Sediment Discharge from a Bordered Road Plot using a Settling Basin and Tipping

Bucket. USDA Forest Service Rocky Mountain Research Station, Boise, Idaho. Available at http://www.fs.fed.us/GRAIP/downloads/New%20road%20plot%20v3.pdf

Coe, D.B.R. 2006. Sediment production and delivery from forest roads in the Sierra Nevada, California. M.S. Thesis, Colorado State University, Fort Collins, CO. 110 p.

Gray, John R., G. Douglas Glysson, Lisa M. Turcios, and Gregory E. Schwartz. 2000. Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data. Water-Resources Investigations Report 00-4191. USGS: Reston, VA.

Ish, Teresa, and David Tomberlin. 2007. Simulation of surface erosion on a logging road in the Jackson Demonstration State Forest. In *Proceedings of the Redwood Science Symposium*, Standiford, R., et al., eds. U.S. Forest Service General Technical Report PSW-GTR-194. pp. 457-463.

Korte, A. and L.H. MacDonald. 2007. Preliminary summary: sediment production and delivery in the southern Sierra Nevada. Unpubl. Paper dated 1 March, 2007. Watershed Science Program, Colorado State University, Fort Collins, CO. 5 p. plus figures.

Wosika, E.P. 1981. Hydrologic properties of one major and two minor soil series of the coast ranges of Northern California. Arcata, CA: Humboldt State Univ.; 150 p. M.S. thesis. Available at http://www.fs.fed.us/psw/rsl/projects/water/WosikaMS.pdf