THESIS

SEDIMENT PRODUCTION AND DELIVERY FROM FOREST ROADS IN THE SIERRA NEVADA, CALIFORNIA

Submitted by

Drew Bayley Rogers Coe

Department of Forest, Rangeland, and Watershed Stewardship

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DREW BAYLEY ROGERS COE ENTITLED "SEDIMENT PRODUCTION AND DELIVERY FROM FOREST ROADS IN THE SIERRA NEVADA, CALIFORNIA" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

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Adviser

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Department Head

ABSTRACT OF THESIS

SEDIMENT PRODUCTION AND DELIVERY FROM FOREST ROADS IN THE SIERRA NEVADA, CALIFORNIA

Sediment production and sediment delivery from unpaved forest roads was assessed in the Sierra Nevada of California from 1999 to 2002. Sediment production was measured on 27-65 road segments over 3 years in a mixed rain-snow regime. Sediment delivery was evaluated by conducting a detailed survey of 20 km of unpaved roads with 285 distinct road segments.

Sediment production rates varied greatly between years and between road segments. Sediment production rates from native surface roads were 12-25 times greater than from rocked roads. On average, recently-graded roads produced twice as much sediment per unit of storm erosivity as roads that had not been recently-graded. Unit area erosion rates were 3-4 times higher in the first wet season than in either of the following two wet seasons, as the first wet season had near normal precipitation and a higher proportion of rainfall. An empirical model using the product of road segment area and slope (A*S), annual erosivity, and the product of road segment area and a binary variable for grading (A*G) explained 56% of the variability in sediment production. Road sediment production is best mitigated by rocking native surface roads, decreasing sediment transport capacity by improving and maintaining drainage, and avoiding sites where unusual soil characteristics increase road surface or ditch runoff.

Twenty-five percent of the surveyed road length was connected to the channel network. Stream crossings accounted for 59% of the connected road segments, and gullying accounted for another 35% of the connected road segments. The travel distance of sediment below road drainage outlets was controlled by the presence or absence of gullies, soil erodibility, traffic level, and road segment length. The amount of sediment delivered from episodic gully erosion below road segments (0.6 Mg km^{-1} yr^{-1}) is comparable to the amount of sediment being delivered from the road surface (1.4 Mg km^{-1} yr^{-1}).

An analysis of the data from this and other studies shows that road-stream connectivity is strongly controlled by mean annual precipitation and the presence or absence of engineered drainage structures (R^2=0.92; p<0.0001). Road sediment delivery can be minimized primarily by reducing the number of stream crossings, rocking the approaches to stream crossings, reducing the length of roads draining to stream crossings, and minimizing gully formation below drainage outlets.

Drew Bayley Rogers Coe
Department of Forest, Rangeland, and Watershed Stewardship
Colorado State University
Fort Collins, CO 80523
Spring 2006

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1.0. INTRODUCTION

Sediment is one of the most common causes of water quality impairment for streams and rivers in the U.S. (http://oaspub.epa.gov/waters/national_rept.control#TOP_IMP). Unpaved roads are the dominant source of surface erosion in many forested landscapes (Megahan and Kidd, 1972; Reid and Dunne, 1984; Bilby et al. 1989; Luce and Black, 1999). Road-derived sediment has been shown to increase turbidity and suspended sediment concentrations, alter channel substrate and morphology, and adversely affect water quality (Cederholm and Reid, 1981; Bilby et al., 1989; Waters, 1995). Data on road erosion and sediment delivery rates are critical for assessing road impacts on aquatic resources, and a sound understanding of road erosion processes is needed to minimize road sediment production and delivery.

Since 1999 researchers from Colorado State University have attempted to quantify hillslope erosion rates in the Sierra Nevada of California. Sediment fences (Robichaud and Brown, 2002) were used to measure sediment production rates from roads, timber harvest, wildfires, prescribed fires, and recreational off-highway vehicle use. The initial data showed median sediment production rates from roads were nearly an order of magnitude higher than any other source except a recent high-severity wildfire (MacDonald et al., 2004) (Figure 1.1). Given that unpaved forest roads are a ubiquitous feature in the Sierra Nevada landscape, the goal of this study was to quantify sediment production and sediment delivery from unpaved forest roads.

There is a paucity of data on road sediment production and delivery in the Sierra Nevada of California. Regional knowledge on the magnitude and controls of these processes is important for site-scale mitigation of road erosion and sediment delivery. Data on road erosion rates and sediment delivery are vital for assessing and predicting cumulative watershed effects.

In this thesis Chapter 2 examines sediment production from unpaved forest roads, and Chapter 3 examines the delivery of sediment from unpaved forest roads to the channel network. The overall objectives were to: (1) measure sediment production rates from unpaved roads over three wet seasons; (2) identify the dominant controls on road sediment production and develop predictive models; (3) document and quantify the hydrologic and sediment pathways that control the delivery of sediment from unpaved roads to the channel network; and (4) compare connectivity results from the Sierra Nevada with data from other studies.

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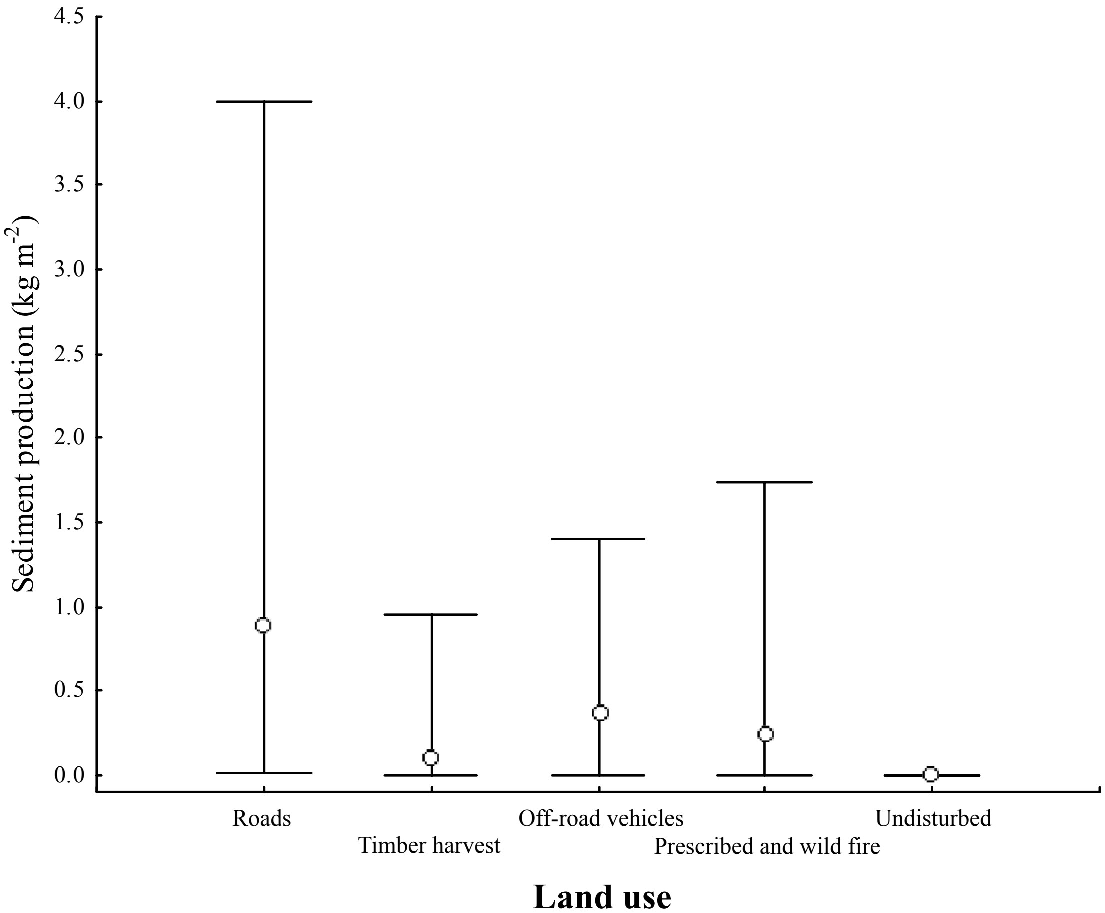

Figure 1.1. Mean and range of sediment production rates by type of land use. Circles represent the mean and bars indicate the range of measured values (from MacDonald et al., 2004).

2.0. SEDIMENT PRODUCTION FROM FOREST ROADS IN THE SIERRA NEVADA

ABSTRACT:

This study used sediment fences to measure sediment production from 27-65 road segments over three wet seasons in the Sierra Nevada of California. The first wet season had near-normal precipitation and annual storm erosivity (EI_A). The second and third wet seasons had below normal precipitation, and EI_A was less than 50% of the long-term mean as most of the precipitation fell as snow rather than rain. The mean sediment production rate from native surface roads was 0.81 kg m^{-2} in the first wet season versus 0.22 and 0.23 kg m^{-2} in the second and third wet seasons, respectively. The median sediment production rate from ungraded native surface roads was 15 times greater than rocked roads. Comparisons among segments showed that recently-graded native surface roads produced twice as much sediment per unit storm energy as ungraded native surface roads. Sediment production on native surface roads was best predicted by the product of road area times road slope (A*S), annual erosivity, and the product of road area and a binary variable for grading (A*G) (R^2=0.56). Normalized sediment production rates on mid-slope roads increased with decreasing soil depth. This increase is attributed to the greater interception of subsurface stormflow and resulting increase in road surface runoff. Road sediment production can be reduced by rocking native surface roads, increasing the frequency of road drainage structures, avoiding locations that generate more road surface and ditch runoff, and minimizing grading and traffic. The study illustrates the difficulties of predicting road erosion rates, particularly in a mixed rain-snow climate.

2.1. INTRODUCTION

Unpaved roads are the dominant source of surface erosion in many forested landscapes (Megahan and Kidd, 1972; Reid and Dunne, 1984; Bilby et al. 1989; Luce and Black, 1999). Road-derived sediment has been shown to increase turbidity and suspended sediment concentrations, alter channel substrate and morphology, and adversely affect water quality (Cederholm and Reid, 1981; Bilby et al., 1989; Waters, 1995). Data on road erosion and sediment delivery rates are critical for assessing road impacts on aquatic resources, and a sound understanding of road erosion processes is needed to minimize road sediment production.

Several studies have identified unpaved roads as a major sediment source in the Sierra Nevada of California, but none of these studies directly measured road erosion rates. Forest roads were estimated to contribute 74% of the sediment produced from a 194 km^2 catchment in central Sierra (Euphrat, 1992), and 19% of the sediment yield for a 6.8 km^2 catchment in the southern Sierra (Reid and Dunne, 1996). Both of these studies used the Universal Soil Loss Equation (USLE) to estimate sediment production rates. Unpaved roads have the highest disturbance coefficient in the methodology used to assess cumulative watershed effects on national forest lands in California (Cobourn, 1989), but there are no data on either the relative or the absolute contribution of unpaved roads to landscape-scale sediment production rates in the Sierra Nevada.

The extrapolation of road erosion rates to the Sierra Nevada from either the Pacific Northwest (Reid and Dunne, 1984; Bilby et al., 1989; Luce and Black, 1999; Luce and Black, 2001a) or the Idaho batholith (Megahan and Kidd, 1972; Megahan, 1974; Burroughs and King, 1989) is uncertain given the mixed rain-and-snow regime and the relative lack of winter traffic. The freezing level of winter storms usually fluctuates between 1000 m and 2500 m (Kattelmann, 1996), and this causes a corresponding fluctuation in the depth and extent of snow cover. As a result, the erosive energy available for sediment detachment and sediment transport changes according to whether the precipitation falls as rain or snow (Cooley et al., 1988).

Given the lack of data on road erosion rates in the Sierra Nevada and the concern over anthropogenic sediment inputs (Millar, 1996), there is an urgent need to quantify road sediment production rates and road erosion processes. A better knowledge of the magnitude and controls of road erosion processes is important for site-scale mitigation of road erosion. Furthermore, data on road erosion is vital for assessing and predicting cumulative watershed effects. With these considerations in mind, the objectives of this study were to: (1) measure sediment production from ungraded native surface roads, recently-graded roads, and rocked roads in mid-elevation areas in the central Sierra Nevada; (2) determine the temporal variability in road sediment production rates within and between winter wet seasons; (3) identify the dominant controls on road sediment production; and (4) develop empirical models for predicting road sediment production.

2.2. BACKGROUND

Sediment production from unpaved roads is a function of the erosive energy applied to the road surface and the erodibility of the road surface (Luce and Black, 1999; Ziegler et al., 2000a; Luce and Black, 2001a). Erosion from road surfaces can be partitioned into rainsplash and hydraulic components (Ziegler et al., 2000a):

$$e = e_s + e_h \tag{2.1}$$

where e is the net erosion rate from the road surface, e_s is rainsplash erosion, and e_h is the hydraulic erosion from overland flow. Rainsplash erosion results from the force of falling raindrops and is a function of storm intensity, raindrop size, storm depth, and soil erodibility (Wischmeier and Smith, 1978; Brown and Foster, 1987; Renard et al., 1997).

Hydraulic erosion is a function of the sediment transport capacity of overland flow and can be expressed by:

$$e_h = k\,(\tau - \tau_c)^{n} \tag{2.2}$$

where k is an index of the erodibility of the soil, τ is the shear stress applied by overland flow, τ_c is the soil's critical hydraulic shear strength, and n is an exponent between 1 and 2 (Kirkby, 1980; Nearing et al., 1994). Shear stress is defined as:

$$\tau = \rho_w\, g\, d\, s \tag{2.3}$$

where ρ_w is the density of water, g is the acceleration due to gravity, d is the depth of overland flow, and s is the water surface slope (Wohl, 2000). Since the mean flow depth (d) is a function of discharge (Knighton, 1998), hydraulic erosion is proportional to the amount of road surface runoff.

Road surface runoff is typically generated by Horton overland flow (HOF) plus the interception of subsurface flow (ISSF) by road cutslopes (Megahan, 1972; Luce and

Cundy, 1994; Ziegler and Giambelluca, 1997; Ziegler, 2001c; Wemple and Jones, 2003). Hence, total road surface runoff (Q_t) can be described as:

$$Q_t = Q_{HOF} + Q_{ISSF} \qquad (2.4)$$

where Q_{HOF} is the runoff due to HOF generation and Q_{ISSF} is the runoff due to ISSF. HOF from a road surface is calculated by:

$$Q_{HOF} = (P - I)\ A \qquad (2.5)$$

where P is precipitation intensity, I is the infiltration rate of the road surface, and A is the road surface area.

The volume of Q_{ISSF} is related to upslope soil properties, including the saturated hydraulic conductivity (K_s), depth to bedrock, hillslope gradient, topographic or bedrock contributing area, antecedent moisture conditions, and storm precipitation (Freer et al., 1997; Sidle et al., 1995; Freer et al., 2002; McGlynn et al., 2002; Weiler and McDonnell, 2004). ISSF occurs when the depth of the road cut (D_R) exceeds the depth to the water table (D) (Wigmosta and Perkins, 2001; Wemple and Jones, 2003). Assuming that the soil overlies a relatively impermeable layer, D will be smaller for shallow soils than for deeper soils, and roads crossing shallow soils will have a higher likelihood of intercepting subsurface flow. Conversely, the runoff from roads on deeper soils is more likely to be dominated by Q_{HOF} (Ziegler et al., 2001c).

The dependence of road sediment production rates on the erodibility of the road surface has been well documented (Megahan, 1974; Ziegler et al., 2000; Ziegler et al., 2001a,b; Luce and Black, 2001a,b). Traffic and road maintenance each increase the erodibility (K) of unpaved road surfaces by increasing the abundance of easily detachable sediment (Reid and Dunne, 1984; Ziegler et al., 2000; Luce and Black, 2001b; Ziegler et al., 2001a,b; MacDonald et al., 2001; Ramos-Scharron and MacDonald, 2005). As the more erodible surface material is removed, the road surface coarsens and becomes more resistant to rainsplash and the shear force exerted by overland flow (Ziegler et al., 2000; MacDonald et al., 2001).

Since the unpaved roads in the Sierra Nevada vary widely in terms of traffic, grading, and soil depth, comparisons between years and segments can help elucidate the importance of these different factors and provide insights into the underlying processes. This information can be used to help minimize sediment production from existing roads, guide future road designs, and set priorities for road rehabilitation or road obliteration.

2.3. METHODS

2.3.1. Site Description

The study area lies on the west slope of the Sierra Nevada mountain range in California, and is bounded to the north by the Rubicon River drainage and to the south by the South Fork of the Cosumnes River (Figure 2.1). Elevations range from 910 to 2000 m. The primary forest type is mixed conifer, but this turns to red fir with increasing elevation (SAF, 1980). The Mediterranean-type climate means that nearly all of the precipitation falls between 1 October and 1 June (USDA, 1985). Mean annual precipitation at the Pacific House rain gage at 1036 m is 1300 mm, but the standard deviation is 440 mm and the range over a 60-year period is from 450 mm to 2310 mm. The majority of the study area is from 1000 to 1800 m a.s.l., which is within the rain-on-snow climatic zone (Cobourn, 1989). Most of the study sites were on the Eldorado National Forest, although some sites were on interspersed Sierra Pacific Industries (SPI) property.

The dominant lithologies are weathered granitic batholith, granitic glacial deposits, andesitic lahar (Mehrten formation), and metasediments (USDA, 1985). The soils are typically coarse-textured loams, and contain up to 60% gravel by weight (USDA, 1985). Most of the soils are over a meter thick, but the range of soil depths is from 0.3 to 1.7 m. Soil erodibility (K) factors range from 0.013 to 0.042 t ha h ha^{-1} MJ^{-1} mm^{-1} (USDA, 1985).

2.3.2. Study Design

Sediment production was measured from road segments using sediment fences (Robichaud and Brown, 2002) over three wet seasons (1999-2000, 2000-2001, 2001-2002). Each study segment had a discrete drainage point (e.g., waterbar, rolling dip, or a relief culvert) so that all of the sediment produced from that segment could be captured by one or more sediment fences. Twenty-seven segments were monitored during the first wet season, 47 segments in the second wet season, and 65 segments in the third wet season (Table 2.1). The road segments were stratified into ungraded native surface roads, recently-graded native surface roads, and rocked roads. Ungraded native surface roads were defined as segments that had not been graded or used for timber hauling within the previous two years. Rocked roads were surfaced with approximately 10 cm of coarse gravel. One rocked road segment had its ditch graded prior to the first wet season, while the remaining rocked road segments (n=9) had no recent grading activity (Table 2.1).

Most of the study segments were designed to be outsloped, but repeated grading had formed a berm along the downslope edge of these segments. This berm held the surface runoff on the road segment until it reached a functioning waterbar or rolling dip. In areas with shallow soils and rock outcrops, the roads were generally insloped and had an inside ditch that was drained by a relief culvert. Most of the segments added in the second and third field seasons were on ridgetop roads in order to minimize cutslope erosion and the interception of subsurface stormflow. Traffic loads were not measured directly, but the recently-graded roads had more traffic because grading was generally a prerequisite to timber hauling.

2.3.3. Measurement Procedures

The sediment fences were constructed of geotextile fabric staked with reinforcing steel rods (rebar) 1.3 cm in diameter and 1.2-1.5 m long. Fences were constructed with Amoco 2130 fabric that had an opening size of 0.6 mm and a flow rate of 405 L min^{-1} m^{-2} (Robichaud and Brown, 2002). Multiple fences were constructed below selected road segments to increase storage capacity and sediment trapping efficiency. Fabric aprons were laid down in front of the sediment fences to facilitate the identification and removal of the deposited sediment.

The length and total width of the road segment draining to each fence was measured to the nearest decimeter. The measured width included the width of the road surface and ditch but did not include the width of the cutslope or fillslope. Road segment slope were measured with a clinometer and recorded as a decimal. The lithology and soil type was determined from the Eldorado National Forest Soil Survey (USDA, 1985) and field verified. The mean elevation of the study sites was 1424 m in 1999-2000, and as additional sites were added this gradually increased to 1510 m in 2001-2002. The elevation of individual sites ranged from 1015 m to 1829 m.

Sediment production was determined by excavating the sediment trapped by the sediment fences and weighing it to the nearest 0.1 kg. After weighing, the sediment was mixed and two samples were taken to determine soil moisture content (Gardner, 1986). The mean moisture content was used to convert the field-measured wet weights to a dry mass, and annual sediment production rates were calculated by dividing the mass of sediment by the contributing surface area of the road segment. Many sites were not accessible during the winter, so the primary data set consists of annual sediment production rates.

Hydrologic data were obtained at three locations (Figure 2.1). Precipitation was measured at Pacific House (PH) at 1036 m with a tipping bucket rain gage that had a resolution of 1.0 mm (http://cdec.water.ca.gov/cgiprogs/staMeta?station_id=PFH). The Pacific House gage is believed to be representative of the entire study area because wet season precipitation is derived from large frontal storms. Snowpack data were taken from the Robbs Powerhouse SNOTEL site (RP) at 1570 m (http://cdec.water.ca.gov/cgi-progs/staMeta?station_id=RBP) (Figure 2.1). Mean daily discharge data were taken from the Michigan Bar gaging station on the Cosumnes River (MB) (http://cdec.water.ca.gov/cgi-progs/staMeta?station_id=MHB), as this drains the southern half of the study area. Although this station is only at 51 m a.s.l., the Cosumnes is the only undammed river in or near the study area and the discharge data at Michigan Bar closely reflect both the magnitude and type of precipitation in the study area.

For each wet season the maximum storm erosivity and annual erosivity were calculated from the rainfall data at Pacific House. Individual storms were defined as precipitation events separated from each other by at least 6 hours (Mutchler et al., 1994). The erosivity (EI_{30}) for each storm was calculated by multiplying the total storm energy (E) by the maximum 30-minute rainfall intensity (I_{30}), (Renard et al., 1997). The total energy (E) for each storm was calculated by multiplying the rainfall energy (e_r) by total storm depth (P). The rainfall energy (e_r) for each storm was calculated by the equation developed for the western U.S. (Brown and Foster, 1987):

$$e_r = 0.29\ [1-0.72^{(-0.05i)}] \qquad (2.6)$$

where i is average rainfall intensity of the storm in mm h^{-1}. The annual erosivity (EI_A) was calculated by summing the EI_{30} values for each wet season.

2.3.4. Statistical Analysis

The primary dependent variable was annual sediment production in kg yr^{-1}. To better assess the effect of the various independent variables, this was normalized by contributing road surface area, road slope, rainfall erosivity, or a combination of these variables (Table 2.2). The significance of each of the independent categorical variables (Table 2.2) was evaluated by post-hoc pairwise comparisons using Tukey's Honestly

Significantly Difference (HSD) (Ott, 1993; STATISTICA, 2003). Sediment production rates were log-transformed for pairwise comparisons when sediment production rates were log-normally distributed. The large sample size for native surface roads (n=109) meant that the sediment production for these segments could be related to each of the continuous independent variables in Table 2 by multiple regression using forward stepwise regression with a selection criteria of α=0.05. The presence or absence of grading was treated as a binary variable. Sources of model errors were explored through residual analyses.

2.4. RESULTS

2.4.1. Road Segment Characteristics

Sediment production was measured from native surface and rocked road segments with a wide range of road surface areas and road gradients. For the native surface road segments, road surface areas ranged from 30 to 2170 m^2 (i.e., 8 to 395 m in length) with a mean of 368 m^2. For rocked road segments the mean road surface area was 29% smaller at 261 m^2, and the range was from 107 to 1022 m^2. The mean road surface area for the recently-graded native surface road segments was 228 m^2 as compared to 561 m^2 for the ungraded native surface road segments. The three segments with the largest road surface area had drainage structures that were no longer functioning and therefore somewhat atypical. The gradients for native surface road segments ranged from 0.02 to 0.21 m m^{-1} with a mean of 0.09 m m^{-1}. Gradients for the rocked road segments were similar (0.05 to 0.20 m m^{-1} with a mean of 0.09 m m^{-1}).

The road segments used to measure road sediment production were typically outsloped and drained by waterbars and rolling dips. Only four of the native surface road segments and one of the rocked road segments (i.e., 15 data points over three wet season) were insloped and drained by inside ditches. Each of these five insloped road segments drained hillslopes with shallow soils less than 0.5 m in depth. The roads were generally under 30-40 years in age, and most had been reconstructed using current best management practices (BMPs) in recent years (D. Arrington, pers. comm., 2000).

2.4.2. Precipitation and Runoff

Annual precipitation in the first wet season was 1290 mm, which is very close to the long-term mean of 1300 mm. In the second and third wet seasons precipitation was only 68% and 82% of the long-term mean, respectively (Figure 2.2). In the first wet season approximately 50% of the annual precipitation fell between 11 January and 14 February, while precipitation in the second and third wet seasons was much more evenly distributed (Figure 2.2).

The total erosivity (EI_A) in the first wet season was 847 MJ mm ha^{-1} hr^{-1}. The EI_A values in the second and third wet seasons were respectively only 441 and 456 MJ mm ha^{-1} hr^{-1}, or less than 60% of the value from the first wet season. In the first wet season the maximum storm erosivity in the first season was 252 MJ mm ha^{-1} hr^{-1} from a 175-mm storm in late January. Since this storm increased the snow water equivalent (SWE) at Robbs Powerhouse by only 4 mm (Figure 2.3), precipitation below this elevation was mostly rain. In the second and third wet seasons the maximum storm erosivity was only 98 and 83 MJ mm ha^{-1} hr^{-1}, respectively.

The SWE data show that the snow cover was thinner and less frequent in the first wet season relative to the second and third wet seasons (Figure 2.3). In 1999-2000 the snowpack at Robbs Powerhouse didn't begin to accumulate until 7 December and meltout occurred by 31 March, resulting in 115 days with snow cover (Table 2.3). SWE was below 70 mm until mid-February, suggesting a lack of snow cover at the lower elevation sites. The peak SWE was 302 mm in the second week of March, which is less than half of the 30-year mean peak SWE of 656 mm.

In the second wet season the first storms were unusually cold and the snowpack began accumulating on 26 October (Figure 2.3). Most of the subsequent precipitation fell as snow, and the SWE steadily increased from mid-December until the peak SWE of 406 mm was reached in early March. Meltout occured on 24 April, indicating 167 days of snow cover (Figure 2.3).

Although some data are missing from the third wet season, by early December there were 150 mm of SWE, indicating that much of the early season precipitation had fallen as snow rather than rain (Table 2.3; Figure 2.3). As in 2000-2001, the snowpack persisted until late April. The greater duration of snow cover in the second and third wet seasons is confirmed by our field observations, as the road segments above 1400 m were generally accessible until mid-February in the first wet season, and largely inaccessible from early January to until late March in both the second and third wet seasons.

The daily discharge data confirm the preponderance of rain and much greater erosivities in the first wet season, as four storms each generated mean daily flows in the Cosumnes River of more than 150 $m^3 s^{-1}$ (Figure 2.4). The largest mean daily flow during the study period was 289 $m^3 s^{-1}$ on 14 February 2000, and this has an estimated recurrence interval of 2.4 years. This peak flow was due to 114 mm of precipitation in 48 hours as measured at the PH rain gage. Since this storm increased the SWE at RP by only 66 mm, almost half of the precipitation below 1570 m fell as rain. Many of the field sites that had been snow covered became accessible during and after this storm, indicating that the high flows were due to a combination of rain and snowmelt.

In the second wet season there were no obvious rain-on-snow events in the annual hydrograph, and the largest daily flow was just 28 $m^3 s^{-1}$ in late March (Figure 2.4). In the third wet season there were four small rain-on-snow events, but the largest daily flow was only 70 $m^3 s^{-1}$, or 24% of the maximum daily flow recorded during the first wet season (Figure 2.4).

2.4.3. Sediment Production Rates by Road Surface Type and Wet Season

The distribution of sediment production rates was highly skewed by a few segments with exceptionally high values (Figure 2.5). For native surface roads the mean annual sediment production rate was 0.32 kg m^{-2} yr^{-1} (Table 2.4), while the median value was only 0.14 kg m^{-2} yr^{-1}. Rates were highly variable as the range for native surface road segments was from 0.0002 kg m^{-2} yr^{-1} to 4.0 kg m^{-2} yr^{-1} (Figure 2.5).

The distribution of sediment production rates for rocked roads was even more skewed, as the overall mean of 0.12 kg m^{-2} yr^{-1} was 13 times the median value of 0.009 kg m^{-2} yr^{-1} (Table 2.4). The larger skew was due primarily to one segment that yielded 3.3 kg m^{-2} yr^{-1} in the first wet season. This is nearly 170 times the mean value of 0.02 kg m^{-2} yr^{-1} for the other 29 segment-years of data. The high sediment production rate from this segment was attributed to the fact that the inboard ditch had been graded during the previous summer, and the upslope area had very thin soils and scattered rock outcrops, resulting in visibly high rates of Q_{ISSF}.

The 2.5-fold difference in the overall mean sediment production rates between the native surface and the rocked roads was significant at $p<0.0001$. Given the large amount of skew in the data, the 15-fold difference in median sediment production rates is a more accurate indication of the effect of rocking on road sediment production.

Sediment production rates varied greatly between wet seasons (Figure 2.5). In the first wet season the mean sediment production rate from native surface roads was 0.81 kg m^{-2}, and this was approximately four times the mean values in the second and third wet seasons. The mean sediment production rate for rocked roads in the first wet season was 0.36 kg m^{-2} (Table 2.4). If the one segment with a recently-graded inside ditch is excluded, the mean sediment production rate for the rocked roads was only 0.03 kg m^{-2} in the first wet season. In the second and third wet seasons the mean sediment production rates for rocked roads was only 0.01 and 0.02 kg m^{-2}, respectively.

2.4.4. Other Controls on Road Sediment Production

For native surface roads the annual rainfall erosivity (EI_A) explained 15% of the variability in sediment production rates between years ($p<0.0001$). Maximum storm erosivity (EI_M) and total precipitation explained 14% and 10% of the variability, respectively. EI_A was not significantly related to sediment production rates for the entire data set of rocked roads, but if the extreme outlier in Figure 2.5 is excluded, EI_A explains 20% of the variability in sediment production rates between years ($p=0.02$). Similarly, total precipitation and EI_M each explained about 20% of the variability for rocked roads once the extreme data point in Figure 2.5 was excluded from the data set.

Several segment-scale variables were important controls on sediment production rates for both native surface and rocked roads. For native surface roads, road surface area explained 33% of the variability in sediment production per unit erosivity ($p<0.0001$) (Figure 2.6a). When treated as a continuous variable, road slope was significantly but weakly related to the normalized sediment production rate (kg m^{-2} EI_A^{-1}) for native surface roads ($R^2=0.04$; $p=0.04$). However, the mean sediment production rate for native surface road segments with slopes ≥7% was approximately 75% higher than segments with slopes less than 7% ($p=0.005$; Figure 2.7).

For the native surface road segments, the product of road surface area and road slope (A*S) explained 44% of the variability in sediment production per unit erosivity. Road surface area times slope (A*S) was more strongly correlated with normalized sediment production rates (kg yr^{-1} EI_A^{-1}) for the steeper roads segments ($R^2=0.56$; $p<0.0001$). Sediment production rates were not significantly related to A*S for the native surface road segments with slopes <7% ($p=0.60$).

For the rocked road segments, road surface area explained 32% of the variability in sediment production rates per unit erosivity. Removing the outlier in Figure 2.5 increased the R^2 for this relationship to 0.87 (Figure 2.6b). Road slope was not significantly related to normalized sediment production (kg m^{-2} EI_A^{-1}) ($p=0.73$). In contrast to the native surface roads, road surface area was more strongly related to the normalized sediment production rates than A*S ($R^2=0.48$; $p=0.01$).

The native surface road segments that had been recently graded produced about twice as much sediment per unit erosivity as the ungraded segments ($p=0.02$) (Figure 2.8). A pairwise comparison indicated that there was no evidence of a decline in sediment production rates between the first and second years after grading ($p=0.86$). Hence the term recently-graded refers to any segment that had been graded within the past two wet seasons.

A more detailed analysis shows that grading has a strong effect on sediment production rates at lower elevations, but not at higher elevations (Figure 2.9). For the native surface roads below 1400 m, the recently-graded segments produced approximately eight times more sediment than the ungraded segments when sediment production rates were normalized by A*S and EI_A ($p=0.0008$). In contrast, grading had no apparent effect on normalized sediment production rates for the native surface roads above 1400 m ($p=0.92$) (Figure 2.9). The recently-graded native surface roads below 1400 m also produced nearly 5 times more sediment than the recently-graded native surface roads above 1400 m, and this difference was highly significant ($p=0.0005$) (Figure 2.9). For the ungraded roads, there was no significant difference in normalized sediment production rates with elevation class ($p=0.14$).

Stepwise multiple regression shows that sediment production from native surface road segments is controlled by the product of road surface area and slope (A*S), annual storm erosivity (EI_A), and the product of road surface area and a binary variable for grading (A*G) that has a value of 1 if the segment has been recently graded and 0 if the segment has not been graded. The resultant model is:

$$SP_{ns} = -329 + 3.56\,(A*S) + 0.542\,EI_A + 0.389\,(A*G) \quad (2.7)$$

where SP_{ns} is sediment production for native surface roads in kilograms per year (Table 2.5). The overall model R^2 is 0.56, the adjusted R^2 is 0.54, and the standard error is 142 kg.

2.5. DISCUSSION

2.5.1. Comparisons to Previous Studies

The mean annual sediment production rate for the native surface road segments ranged from 0.23 to 0.81 kg m^{-2} yr^{-1}, with a 3-year average of 0.32 kg m^{-2} yr^{-1} (Table 2.4). Assuming an average road width of 5.0 m, this converts to 1.6 Mg km^{-1} yr^{-1}. Road erosion rates for unpaved roads with moderate traffic in the Olympic Peninsula in the state of Washington were 41 Mg km^{-1} yr^{-1} (Reid and Dunne, 1984), or approximately 26 times higher than the 3-year mean reported here. The overall mean from the present study is 67% of the reported mean erosion rate of 0.48 kg m^{-2} for unpaved roads in the Idaho batholith (Megahan, 1974). The similarity in road erosion rates for the Sierra Nevada and the Idaho batholith might be attributed to the similarities in lithology and climate.

The mean sediment production rate from rocked roads ranged from 0.01 to 0.36 kg m^{-2} yr^{-1}, but the upper end of this range was due to one road segment that had a recently-graded ditch and exceptionally high runoff rates. If this segment is excluded, the mean sediment production rate from rocked roads was 0.02 kg m^{-2} yr^{-1}, and the maximum value for a single segment was 0.09 kg m^{-2} yr^{-1}. These values fall within the range of

0.01-0.21 kg m^{-2} yr^{-1} for rocked roads in the Idaho batholith (Burroughs and King, 1989), but the mean is much lower than the rate reported from the Olympic Peninsula (Reid and Dunne, 1984). Since there was no wet season traffic and five of the rocked road segments were behind locked gates, the lower sediment production rates for rocked roads in the Sierra may be attributed to the lack of wet season traffic and lower precipitation relative to the Olympic Peninsula. This rationale is consistent with data from the Oregon Coast Range, where rocked roads with no traffic and no recent grading produced less than 0.02 kg m^{-2} yr^{-1} (Luce and Black, 2001b).

2.5.2. Climatic Controls on Rainsplash and Hydraulic Erosion

The lower sediment production rates from the native surface roads in the second and third wet seasons is due to the difference in precipitation as well as the difference in the type of precipitation. The first wet season had larger and more intense rain events as well as more precipitation, and the annual rainfall erosivity in the first wet season was nearly double the value in the second and third wet seasons. Perhaps more importantly, the second and third wet seasons were colder so more of the precipitation fell as snow and there was constant snow cover on most of the sites. Snowfall has minimal erosive energy when it hits the soil surface (Cooley et al., 1988), and snow cover protects the road surface from rainsplash erosion during rain-on-snow events.

Previous research suggests that rainsplash erosion accounts for approximately 50% of the total erosion from unpaved roads (Ulman and Lopes, 1995; Ziegler et al., 2000), and that erosion rates are linearly related to rainfall erosivity (Renard et al., 1997). Since the EI_A in the second and third wet seasons was roughly 50% of the value from the first wet season, if road surface erosion is proportional to rainfall erosivity the sediment production rates in the second and third wet seasons should have been about half of the value from the first wet season. However, the sediment production rates from native surface roads in the second and third wet seasons were roughly one-quarter of the value from the first wet season, or about half of the expected value. This suggests that the more continuous snow cover during the second and third wet seasons may have reduced the amount of rainsplash erosion (e_s) and/or hydraulic erosion (e_h) by an additional 50 percent.

The reduction in e_s due to a shift from rain to snow is self evident, but the effect of this shift on e_h is more complex. Maximum snowmelt rates in the alpine Sierra are on the order of 30 mm d^{-1} (Kattelmann and Elder, 1991), while rainfall inputs can exceed 100 mm d^{-1}. The lower intensity of snowmelt inputs will reduce both the depth and velocity of overland flow and hence e_h. The presence of a snowpack on the road surface should also reduce the velocity of overland flow, but there are no data on this effect. The prediction of road erosion rates is further complicated by the observation that rills up to 10 cm wide can develop under the snowpack.

The amount of runoff on the road surface also will vary with the amount of Q_{ISSF} (Ziegler et al., 2001c; Wemple and Jones, 2003). For the 17 midslope road segments with data from all three seasons, the normalized sediment production rates (kg $A*S^{-1}$ EI_A^{-1}) decreased with increasing upslope soil depth (R^2=0.17; p=0.002). The relationship between upslope soil depth and normalized sediment production was stronger and slightly more non-linear for the rain-dominated first wet season (R^2=0.32) than the snow-dominated second and third wet seasons (R^2=0.15) (Figure 2.10).

The amount of subsurface stormflow (SSF) varies with upslope soil depth and antecedent soil moisture conditions (Sidle et al., 1995; Freer et al., 1997; Freer et al., 2002; Tromp-van Meerveld and McDonnell, 2006b). SSF is threshold driven, in that it requires subsurface saturation along flowpaths before it can occur (Tromp-van Meerveld and McDonnell, 2006a, 2006b). Subsurface saturation occurs first in shallow soils, and shallow soils can generate SSF during small to medium-size storms (Tromp-van Meerveld and McDonnell, 2006b). In the present study, the first wet season had more precipitation, higher rainfall intensities, and generally wetter soil conditions. I hypothesize that: (1) subsurface saturation occurred on hillslopes more often during the first wet season; and (2) the hillslopes with the shallowest soils produced the most SSF. The larger amount of intercepted SSF in the first wet season resulted in more hydraulic erosion and a stronger relationship between upslope soil depth and sediment production (Figure 2.10). The second and third wet seasons were drier and antecedent soil moisture conditions were presumably lower, resulting in less Q_{ISSF} and a weaker relationship between soil depth and normalized sediment production (Figure 2.10b).

2.5.3. Controls on Road Surface Erodibility and Sediment Supply

Rocking the road surface reduced median sediment production rates by at least an order of magnitude, and this can be attributed to the resulting decreases in e_s, e_h, and the supply of erodible sediment. The 5-20 mm gravel protects against e_s (Burroughs and King, 1989) and greatly increase τ_c (Eq. 2.2). Rocking also increases flow roughness, thereby reducing flow velocities and the erosion due to e_h. Rocking may not be effective if the inside ditch is not rocked, as the highest sediment yield for a single road segment

(3.4 Mg) came from a rocked road segment at 1450 m elevation in the first wet season. This 241 m long, midslope segment intercepted SSF from a hillslope with shallow soils on top of relatively impermeable andesitic lahar deposits (USDA, 1985), and it had a recently-graded inside ditch. Large amounts of Q_{ISSF} were observed from the cutslope during moderate and large rainstorms, and field observations indicated that the amount of Q_{ISSF} changed quickly in response to changes in rainfall intensity. The resultant high flows in the ditch were able to transport cobble-sized clasts (>128 mm). Sediment yields from this segment in the second and third wet seasons were only 1-2% of the value from the first wet season, and this indicates that grading generated a large supply of erodible sediment. These results show that rocking can be a very effective means for reducing road erosion, but in some cases road design, maintenance activities, and local site conditions can negate the usual benefits of rocking the road surface.

The lower sediment production rates from ungraded native surface roads relative to recently-graded roads has been attributed to a more limited supply of easily erodible fine sediment (Ziegler et al., 2000; Ramos-Scharron and MacDonald, 2005). The A*G term in the model (Eq. 2.7) indicates that increase in road sediment production due to grading is proportional to the road surface area, and that a recently-graded road segment produces an additional 0.39 kg per square meter of road surface area than an ungraded road segment.

For some of the more easily-accessible segments, sediment production was measured several times within a wet season. The data from four recently-graded road segments show that sediment production rates per unit precipitation were much higher in the early portion of the wet season (Figure 2.11). The high initial sediment pulse can be attributed to the rapid removal of the thick, fine dust layer that had formed on the road surface as a result of grading and timber hauling activities. The subsequent decline in sediment production per unit rainfall suggests that the recently-graded roads rapidly become supply limited as the road surface becomes armored and more resistant to sediment detachment and transport processes. On the other hand, there was no apparent decline in sediment production rates per unit erosivity between the first and second years after grading. The lack of a decline may be due to continuing high traffic loads on many of recently-graded roads, as the combination of grading and harvesting increased the amount of traffic from firewood cutters and recreationists, and the high traffic levels increase the amount of readily-erodible sediment (Ziegler et al., 2001a.). Wheel ruts also began to appear on many of these roads, and the concentrated flow in these ruts also can increase sediment production rates (Foltz and Burroughs, 1990).

Figure 2.9 shows that grading had no effect on sediment production on road segments above 1400 m in elevation. The lack of a grading effect above 1400 m can be attributed to the fact that most of the precipitation falls as snow and there is more continuous snow cover. This shields the erodible dust layer from e_s and e_h, and this apparently minimizes the effects of grading on sediment production.

The effects of lithology and soil erodibility on road sediment production were difficult to discern given the interacting and confounding effects of the other controlling factors. The mean normalized sediment production from road segments on metasediments was four times greater than segments on other lithologies (p=0.0001). However, there were only four data points for road segments on metasediments, and each of these road segments had been recently graded. Soil erodibility was positively correlated with normalized sediment production (kg $A*S^{-1}$ EI_A^{-1}) for recently graded native surface roads (R^2=0.19; p=0.0004) (Figure 2.12), but not for ungraded native surface roads or rocked roads. These results suggest that erodibility indices such as lithology and soil erodibility tend to have a secondary influence compared to other variables such as A*S, rainfall erosivity, and grading. Lithology and soil erodibility were only significant when the road surface has been recently disturbed by grading and sediment production rates are relatively high. Lithology and soil erodibility are less likely to be good predictors of sediment production once the road surface is armored.

2.5.4. Model Performance and Implications for Long-term Road Erosion Rates

The empirical model presented in equation 2.7 accounts for 56% of the variability in sediment production rates from native surface roads (Figure 2.13). The model is much better at predicting sediment production rates for road segments with a slope ≥7% (R^2=0.62; p<0.0001) than for segments with slopes <7% (R^2=0.21; p=0.01). The greater predictability for the steeper segments can be partly attributed to the significant relationship between A*S and normalized sediment production (kg EI_A^{-1}) for the steeper segments (R^2=0.56; p<0.0001). In contrast, the normalized sediment production rates for road segments with slopes of less than 7% are not significantly related to A*S (R^2=0.01; p=0.60). The significant relationship for the steeper roads does not appear to be due to the greater spread in A*S data, as some of the flatter road segments also have relatively large A*S values. Other studies have suggested that an increase in road length does not necessarily lead to higher sediment production rates for flatter segments (Luce and Black, 1999; Ramos-Scharron and MacDonald, 2005).

The inclusion of A*S in equation 2.7 indicates that sediment production is a linear function of road surface area and slope. However, the normalized sediment production rates (kg m^{-2} EI_A^{-1}) for ungraded road segments are most strongly related to segment slope raised to the 1.9 power (R^2=0.23; p=0.0007). An exponent of 1.9 is close to the values of 1.5-2.0 reported in other studies (Luce and Black, 1999; Ramos-Scharron and MacDonald, 2005). However, sediment production for the entire dataset is best predicted by a linear function of A*S rather than a non-linear function of A*S.

The empirical model in equation 2.7 doesn't include all of the factors that appear to affect road erosion rates. For example, upslope soil depth was not significant in the overall model, and this may be partly due to the fact that 84% of the data came from ridgetop roads where sediment transport capacity is controlled by Q_{HOF} rather than Q_{ISSF}.

The empirical model also doesn't include a factor for elevation, even though road erosion rates significantly decline with increasing elevation for the recently-graded road segments. This decline is due to the shift from rain to snow and the corresponding increase in the frequency of snow cover. The overall model R^2 increased from 0.41 to 0.54 when EI_A was included, as this accounted for much of the difference in sediment production rates between years. However, EI_A was only measured in one location so it could not account for the spatial variability in rainfall erosivity and snow cover. Since the model doesn't include an elevation term it will tend to underpredict sediment production rates from the road segments at lower elevations. Including site-specific EI_A data could potentially improve the performance of the model.

The empirical model in equation 2.7 provides a useful first estimate of road erosion rates for native surface roads in the northern Sierra, but the measured and predicted road erosion rates are probably low relative to the long-term average. Road erosion studies in other areas have shown that the largest storm events generate most of the erosion (Luce and Black, 2001a; Ramos-Scharron and MacDonald, 2005). In the study area the long-term mean EI_A is between 1020 and 1360 MJ mm ha^{-1} hr^{-1} (Renard et al., 1997), or approximately 20-60% more than the EI_A in the first wet season and 220-310% more than the EI_A in the second and third wet seasons. According to equation 2.7, an ungraded native surface road segment with an average road surface area of 368 m^2 and an average slope of 0.09 m m^{-1} would generate 526 kg of sediment in a year with an EI_A of 1360 MJ mm ha^{-1} hr^{-1}, but only 248 kg in the first wet season when the EI_A was 847 MJ mm ha^{-1} hr^{-1}.

The potential underprediction of road erosion rates may be even greater for the midslope roads, as the record peak flow at Michigan Bar in January 1997 was more than eight times the largest instantaneous peak flow recorded during the study period. The magnitude of SSF can increase by a factor of 75 once hillslope hydrologic connectivity is achieved (Tromp-van Meerveld and McDonnell, 2006b). Given that normalized road erosion showed a non-linear relationship with upslope soil depth in the first wet season, this non-linear relationship is likely to be even more pronounced during wetter years. As a result, one would expect a large increase in erosion due to Q_{ISSF} during wetter years, particularly on the road segments that have a cutbank draining shallow soils.

2.5.5. Implications for Management

This study shows that sediment production rates are at least an order of magnitude lower from rocked roads than native surface roads. Rocking decreases rainsplash erosion

(Eq. 2.1), increases the critical shear stress necessary for erosion (Eq. 2.2), and reduces the supply of easily erodible sediment.

The empirical model (Eq. 2.7) indicates that the product of road surface area and road gradient is an important control on road erosion. However, the model also suggests that sediment production is a linear function of A*S, and that frequent road drainage does not necessarily reduce unit area road erosion. Logic still suggests that sediment production rates can be decreased by reducing road contributing area, as this is consistent with erosion theory and other research (Luce and Black, 1999; Luce and Black, 2001a; Ramos-Scharron and MacDonald, 2005). Frequent road drainage also can reduce the likelihood of sediment delivery to the channel network (Wemple et al., 1996; Croke and Mockler, 2001).

Road surface area can be decreased by increasing the frequency of drainage structures such as waterbars or cross-relief culverts, or by outsloping the road surface. In the study area the periodic grading of outsloped roads often has created berms along the downslope edge of the road segment. By keeping the overland flow on the road surface, these berms effectively increase A*S and hence the sediment production rate. Both road drainage structures and outsloping must be maintained if one wishes to minimize surface runoff and reduce road sediment production.

Rocking and drainage are particularly critical for road segments on hillslopes with shallow soils and rock outcrops, as these site characteristics tend to increase the proportion of rainfall and snowmelt that becomes surface runoff. The resulting increase in runoff will increase erosion from cutslopes, inside ditches if present, and the road surface. Soil depth data are generally available from soil surveys, and these data can help land managers identify the soil types and sites that are most susceptible to Q_{ISSF} and high road surface erosion rates.

The recently-graded roads produced more sediment than ungraded roads. A reduction in the frequency of grading will decrease the supply of easily erodible sediment, and this is particularly important for the lower-elevation roads where the easily erodible surface layer is subjected to more rainfall and higher surface runoff rates. The effects of grading did not appear to diminish over a two year period, but recovery may have been masked by the confounding effect of increased traffic after grading.

2.5.6. Future Research

This study showed that road sediment production rates are a complex response to climate, site, and management factors. A more rigorous and quantitative assessment of these factors will require more controlled, process-based studies. Runoff and erosion rates from the road surface need to be measured on segments with varying upslope soil depths under different antecedent conditions for rain, snowmelt, and rain-on-snow events, respectively. Hillslope piezometers above the road segments would help corroborate the discharge data and determine the relative importance of subsurface stormflow as a function of slope position, upslope drainage area, cutslope height, and soil depth. Storm-by-storm measurements of runoff and sediment production would help indicate the relative importance of Q_{HOF} and Q_{ISSF} on road surface runoff and sediment production rates.

The range and complexity of the interactions between local site conditions (e.g., soil depth, erodibility), road segment properties (e.g., A*S, road maintenance), and climate (e.g., rain vs. snow) have important implications for the use and reliability of spatially-distributed, physically-based models such as WEPP (Water Erosion Prediction Project) (Elliot et al., 1995) and DHSVM (Distributed Hydrologic Soil Vegetation Model) (Bowling and Lettenmaier, 2001; Wigmosta et al., 1994). The accuracy of the model outputs depends upon the representation of the underlying processes. Additional research is needed to help refine the numerical representation of HOF, ISSF, sediment detachment, and sediment transport processes and to help verify these models across a range of climatic and environmental conditions.

2.6. CONCLUSIONS

Sediment production was measured from 139 road segments over 3 years in a mixed rain-snow regime in the Sierra Nevada of California. Sediment production rates varied greatly between years and between road segments. The mean sediment production rate from native surface roads was 0.81 kg m^{-2} in the first wet season as compared to 0.22 and 0.23 kg m^{-2} in the second and third wet seasons, respectively. Sediment production rates from native surface roads were 12-25 times greater than from rocked roads. On average, recently-graded roads produced twice as much sediment per unit of storm erosivity than ungraded native surface roads. An empirical model using the product of road area and road slope, annual erosivity, and the product of road area and a binary variable for grading explained 56% of the variability in sediment production. On midslope roads, normalized sediment production increased with decreasing soil depth.

Most of the interannual variability in sediment production rates can be attributed to differences in the magnitude and type of precipitation, and the resulting effect on rainsplash and hydraulic erosion. The first wet season had near-normal precipitation and much of the precipitation in the lower portions of the study area fell as rain rather than snow. In the second and third wet seasons precipitation was below normal and tended to fall as snow. Unit area erosion rates were 3-4 times higher in the first wet season than the second and third wet seasons due to the higher rainfall erosivity, a less persistent snow cover that helps shield the road surface against rainsplash erosion, and reduced road runoff rates.

Road sediment production is best mitigated by rocking native surface roads, decreasing sediment transport capacity by improving and maintaining drainage, and avoiding sites with soil characteristics that increase road surface and ditch runoff. Grading road surfaces and ditches should be kept to a minimum as this increases sediment production rates. Additional process-based studies are needed to quantify the sources of road and ditch runoff, and to measure the effect of runoff rates on sediment detachment and transport. These data are needed to develop and test spatially-distributed, physically-based road erosion models. Accurate road erosion models are needed to help design effective BMPs and provide guidance for land managers.

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2.7. TABLES AND FIGURES

Wet season	Native surface roads		Rocked roads		
	Ungraded	Recently-graded	Ungraded	Recently-graded	Totals
1999-2000	15	2	9	1	27
2000-2001	15	22	9	1	47
2001-2002	15	40	10	0	65
Totals	45	64	28	2	139

Table 2.1. Number of road segments monitored by wet season and road surface type.

Dependent variables	Independent variables
Sediment production = kg	Road segment slope (S)
Sediment production rate = kg m^{-2}	Road surface area (A)
Normalized sediment production = kg EI_A^{-1}	Road area x slope (A*S)
Normalized sediment production rate = kg m^{-2} EI_A^{-1}	Road area x slope^2 (A*S^2)
Normalized sediment production rate = kg A*S^{-1} EI_A^{-1}	Elevation
	Road grading (categorical)
	Road surface type
	Annual precipitation (P)
	Annual storm erosivity (EI_A)
	Maximum storm erosivity (EI_M)
	Soil series
	Lithology
	Soil depth
	Soil erodibility (K factor)
	Soil texture

Table 2.2. List of dependent and independent variables.

Wet season	Start of snowpack	End of snowpack	Number of days with snowpack	Maximum SWE (mm)
1999-2000	7 Dec	31 March	115	302
2000-2001	26 Oct	24 April	167	406
2001-2002	na*	21 April	na	353

* SWE was 150 mm on 6 December 2001.

Table 2.3. Duration of the snowpack and maximum SWE for each of the three wet seasons. na indicates not available.

Wet season	Native surface roads				Rocked roads			
	Mean ($kg\ m^{-2}$)	St. dev. ($kg\ m^{-2}$)	CV (%)	n	Mean ($kg\ m^{-2}$)	St. dev. ($kg\ m^{-2}$)	CV (%)	n
1999-2000	0.81	1.2	148	17	0.36*	1.00	278	10
2000-2001	0.22	0.3	136	37	0.01	0.01	100	10
2001-2002	0.23	0.28	122	55	0.02	0.02	100	10
Mean or total	0.32	0.56	175	109	0.13*	0.6	462	30

* Removing the one segment with the graded inboard ditch reduces the 1999-2000 mean to 0.03 $kg\ m^{-2}$ and the overall mean to 0.02 $kg\ m^{-2}$.

Table 2.4. Mean, standard deviation, and coefficient of variation (CV) of the sediment production rates for each wet season for native surface and rocked road segments.

Variable	Coefficient	Standard error of coefficient estimate	p-value
Intercept	-329	58.1	<0.0001
A*S (m^2)	3.56	0.380	<0.0001
EI_A (MJ mm ha^{-1} hr^{-1})	0.542	0.100	<0.0001
A*G (m^2)	0.389	0.100	0.0018

Table 2.5. Model parameters for predicting annual sediment (kg) from native surface road segments in the study area. The model R^2 is 0.56, the adjusted R^2 is 0.54, and the standard error is 142 kg.

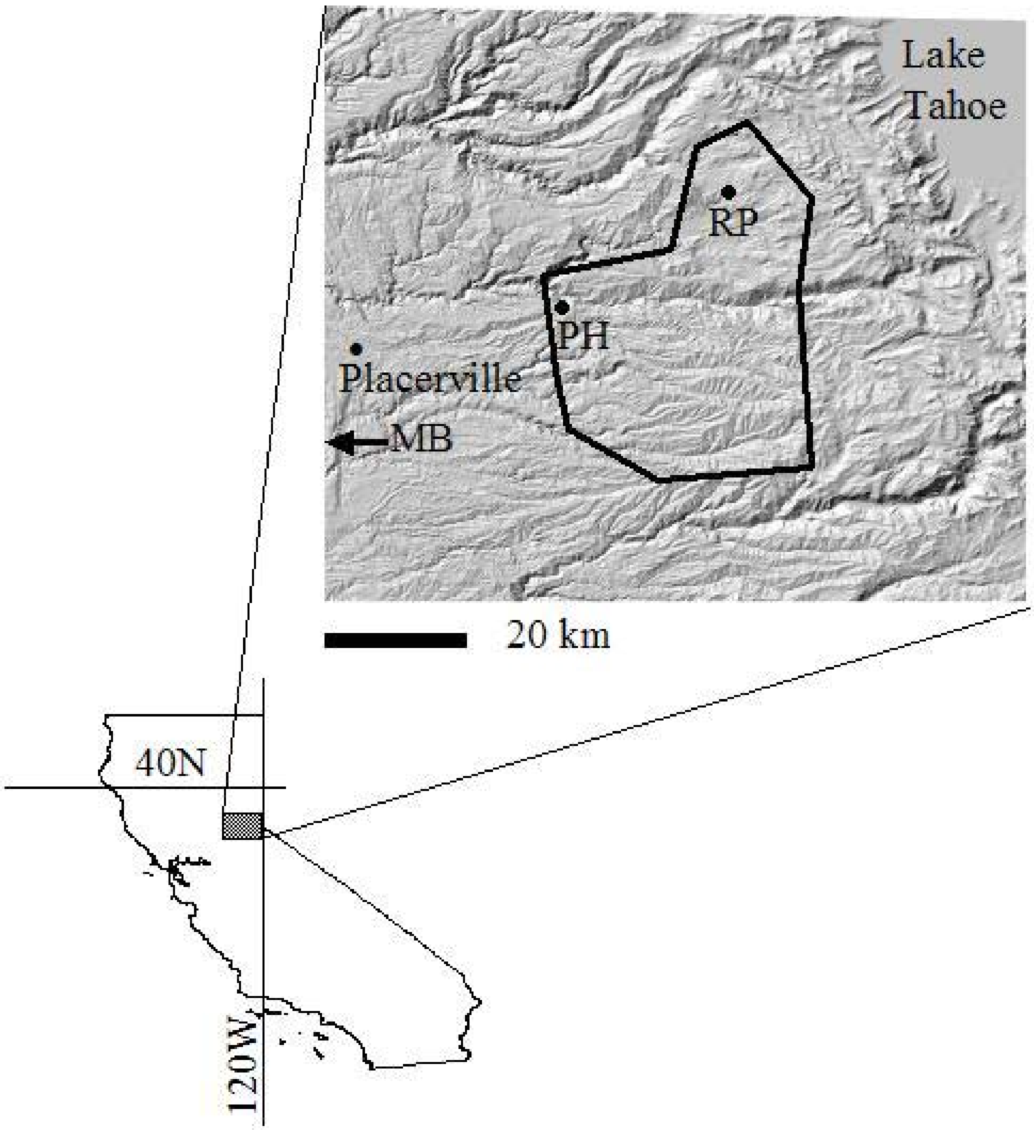

Figure 2.1. Map of the study area. PH is the Pacific House rain gage, RP is the Robbs Powerhouse SNOTEL site, and MB is the Michigan Bar gaging station on the Cosumnes River.

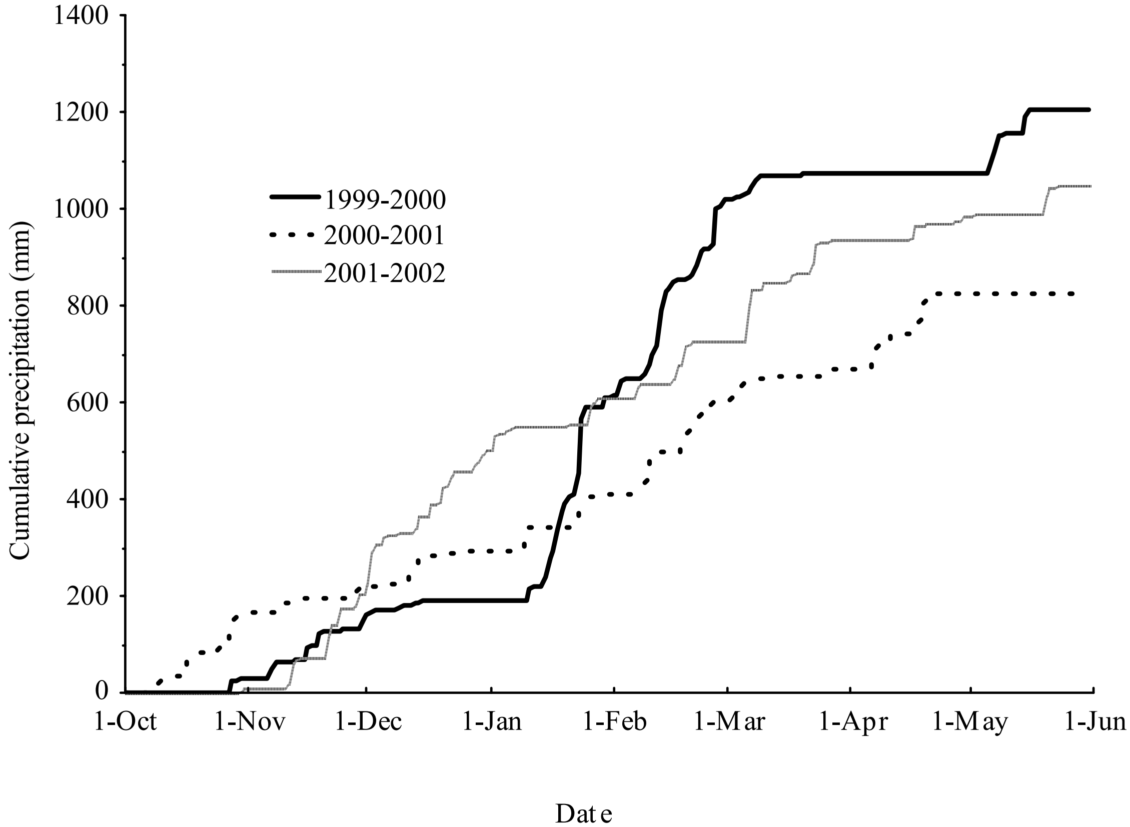

Figure 2.2. Cumulative precipitation at Pacific House from 1 October to 1 June for each of the three wet seasons.

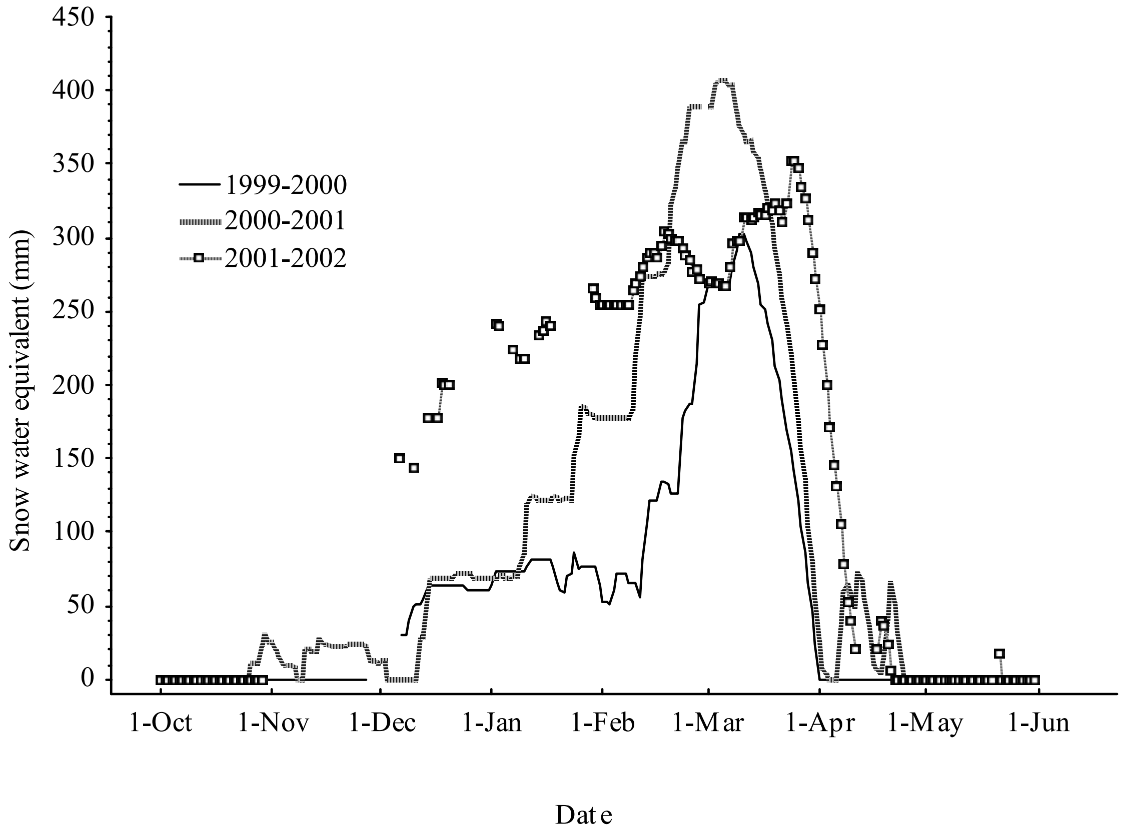

Figure 2.3. Snow water equivalent at Robbs Powerhouse for each of the three wet seasons. Data for 2001-2002 are incomplete.

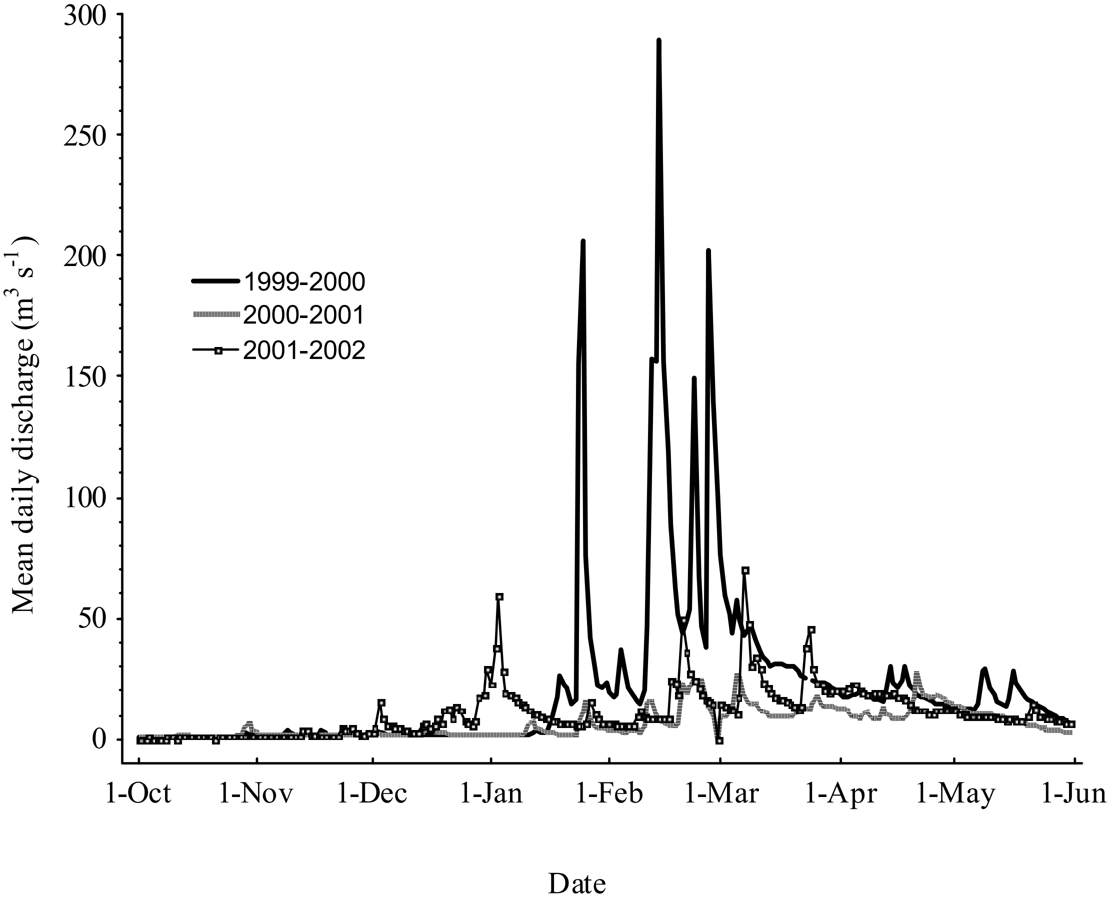

Figure 2.4. Mean daily discharge of the Cosumnes River at Michigan Bar for each of the three wet seasons.

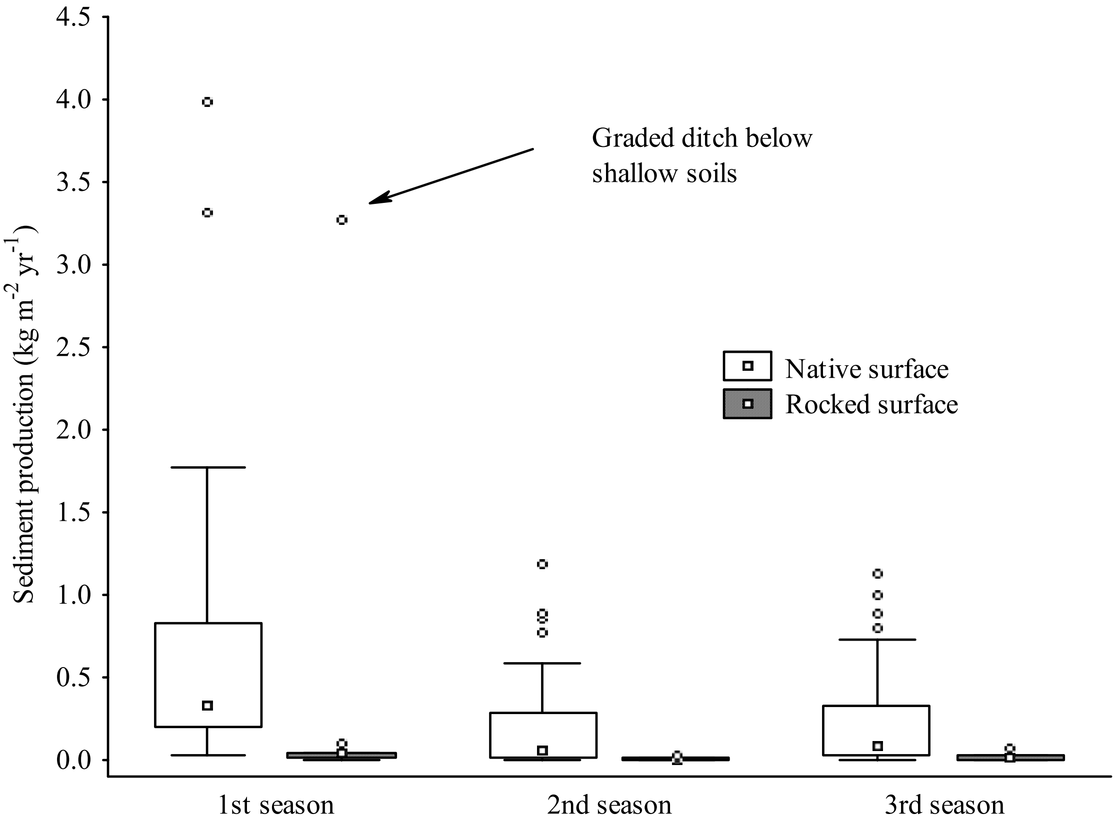

Figure 2.5. Annual sediment production rates for native surface and rocked road segments by wet season. Boxes represent the 25th to 75th quartiles, and the small boxes represent the median value. Circles represent outliers.

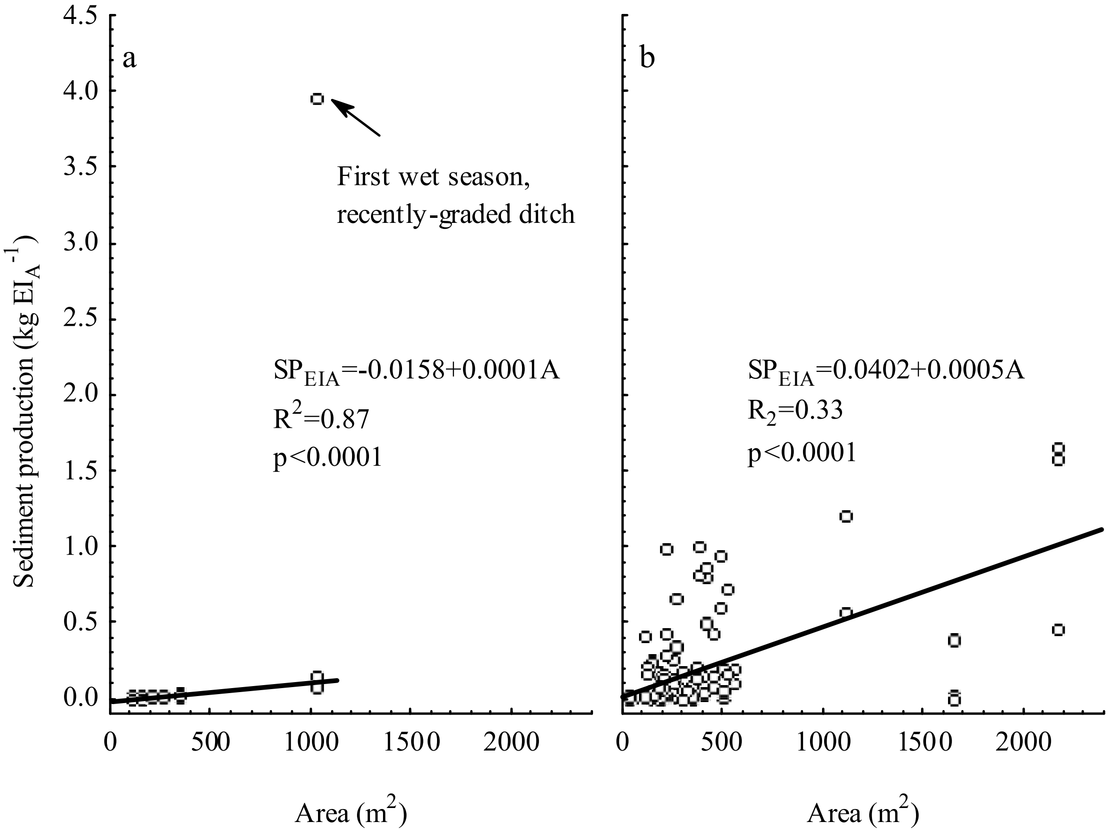

Figure 2.6. Road surface area versus normalized sediment production for: (a) rocked roads, and (b) native surface roads. The data point for the rocked road segment with the graded ditchline is shown, but this point was not included in the regression equation.

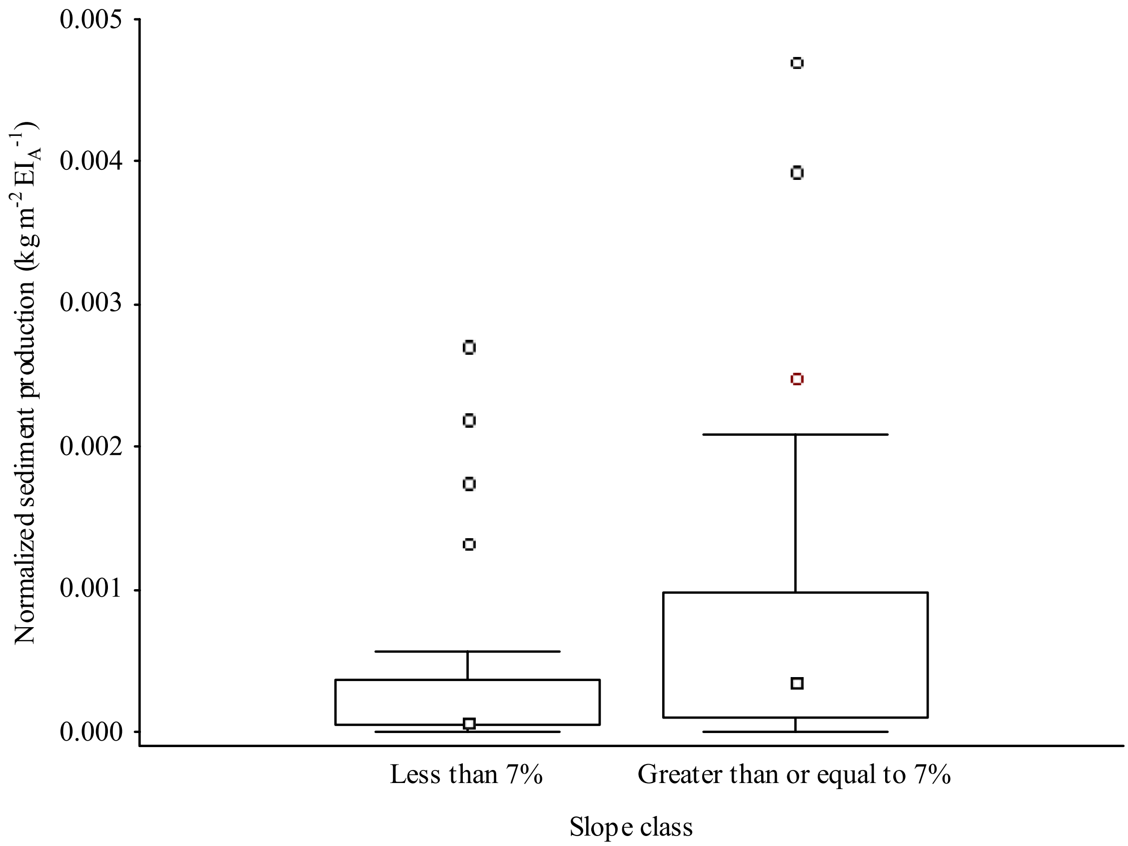

Figure 2.7. Normalized annual sediment production rate for native surface road segments by slope class.

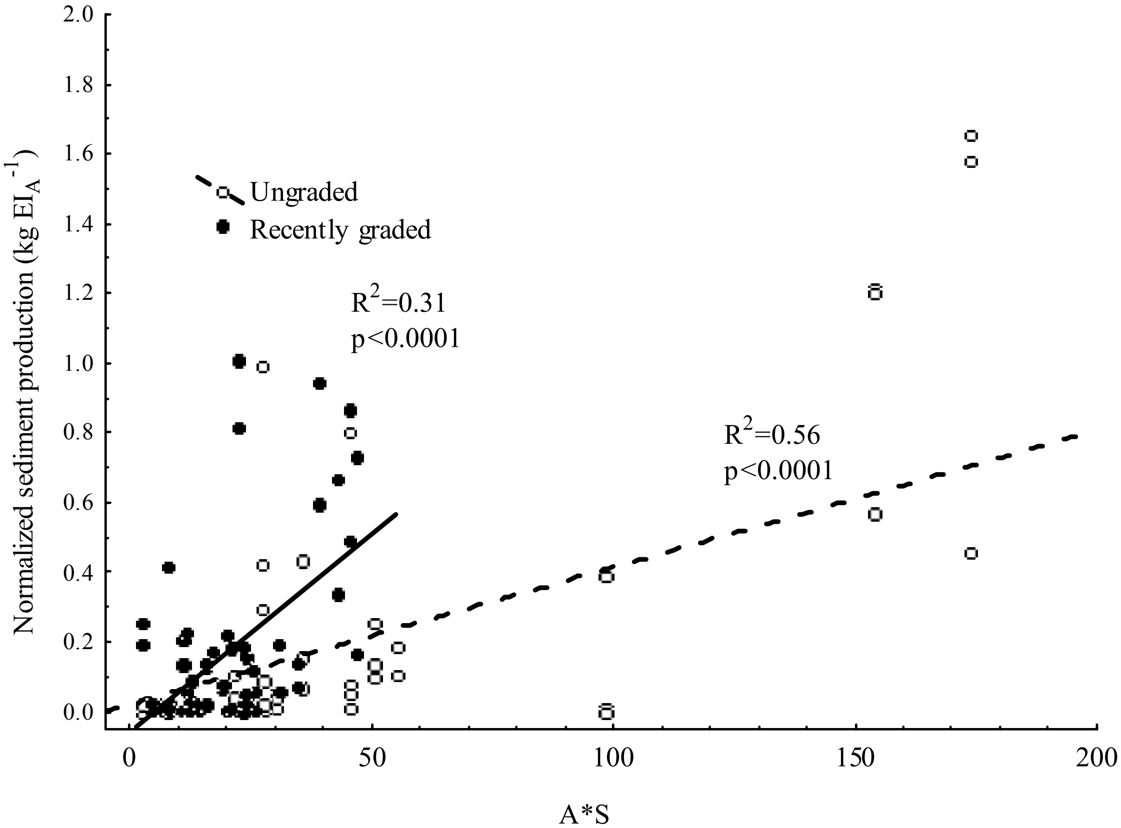

Figure 2.8. Sediment production normalized by EI_A versus road segment area times slope (A*S) for ungraded and recently-graded road segments. Recently-graded roads produce significantly more sediment than ungraded roads when using A*S as a covariate (p=0.02).

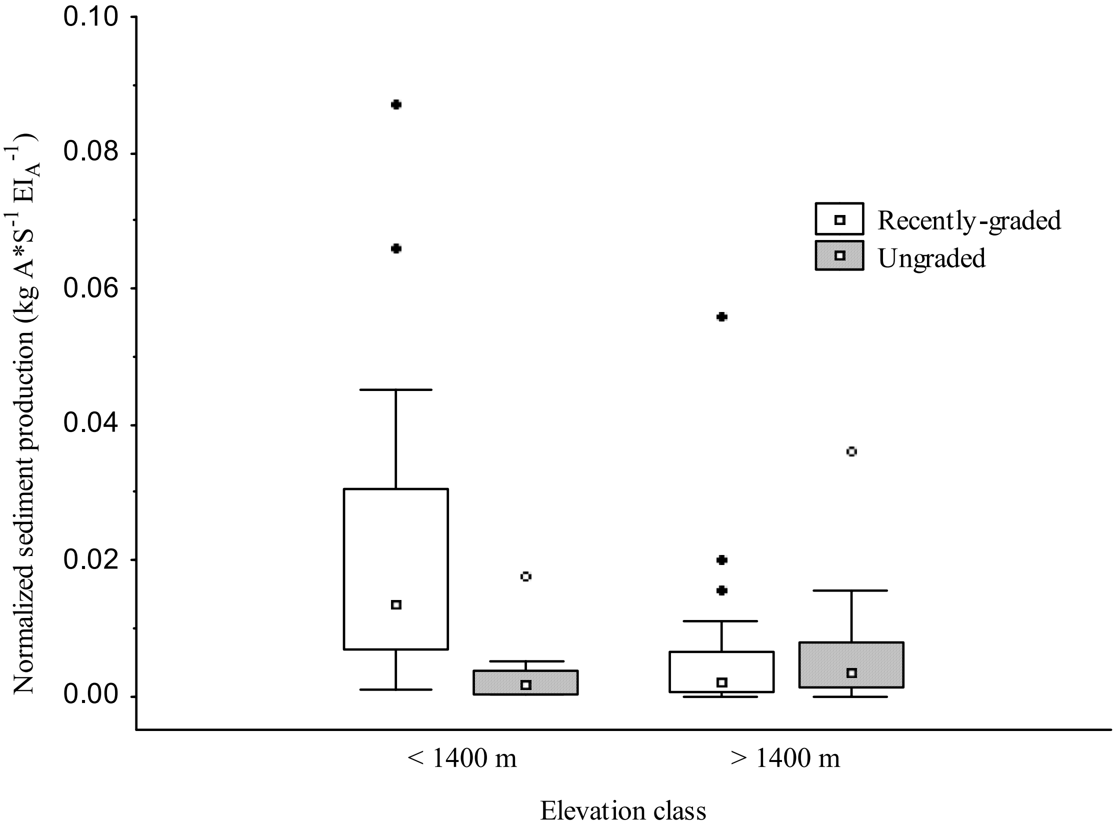

Figure 2.9. Sediment production rates normalized by A*S and EI_A for ungraded and recently-graded road segments by elevation class.

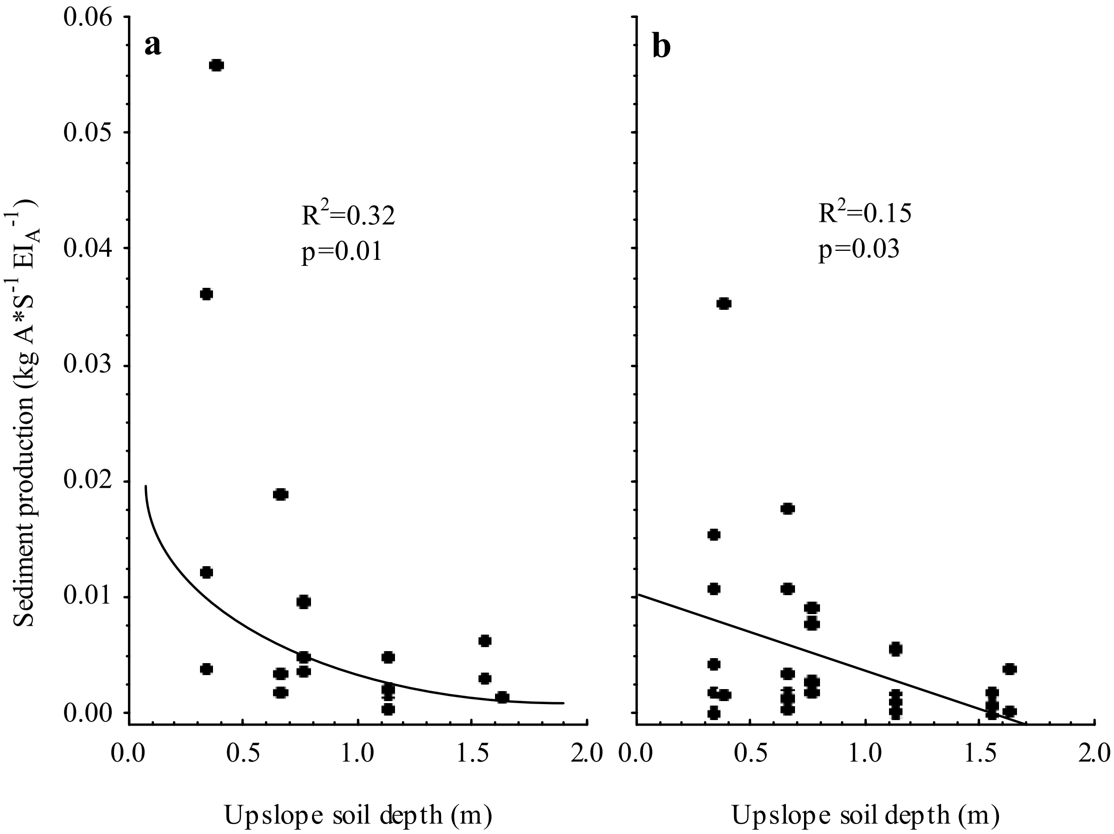

Figure 2.10. Sediment production normalized by A*S and EI_A versus upslope soil depth for midslope road segments in: (a) the first wet season, and (b) the second and third wet seasons.

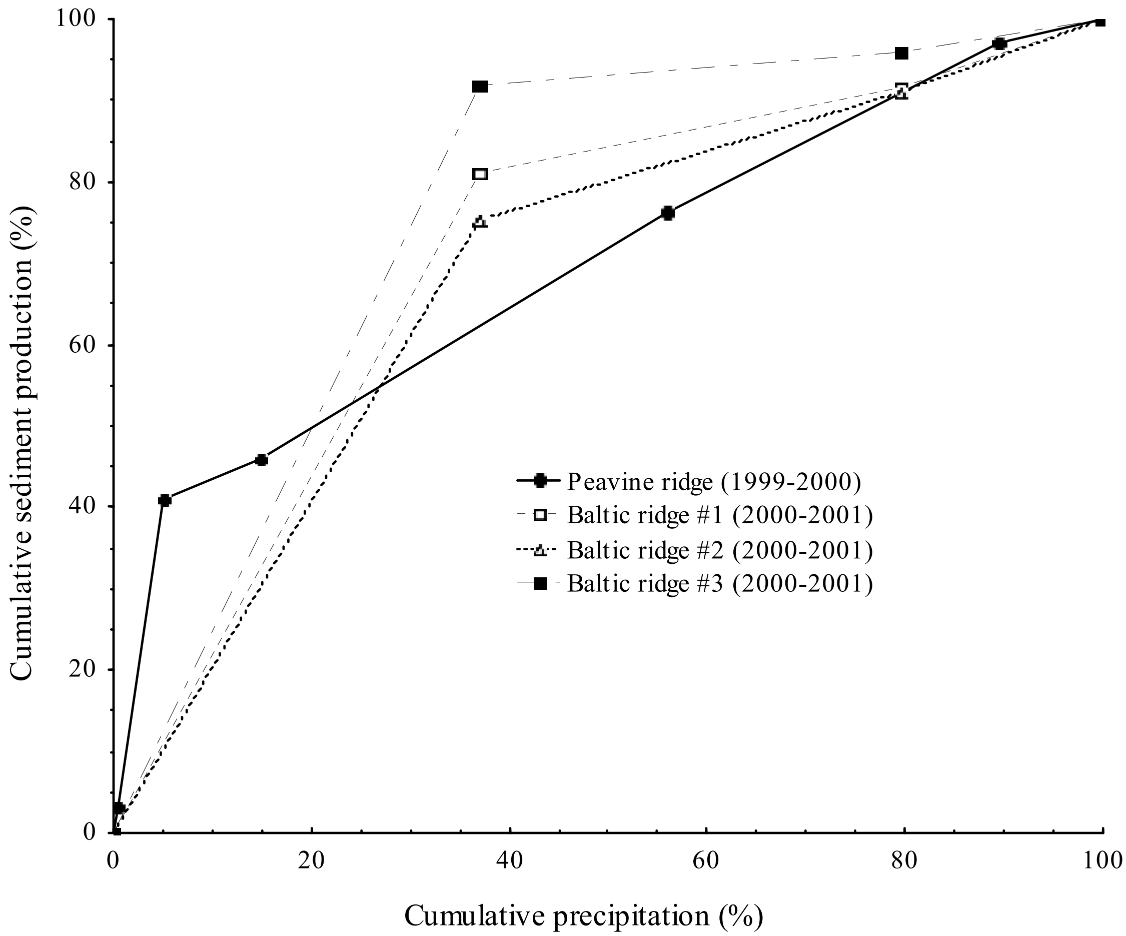

Figure 2.11. Cumulative precipitation versus cumulative sediment production for four recently-graded native surface road segments.

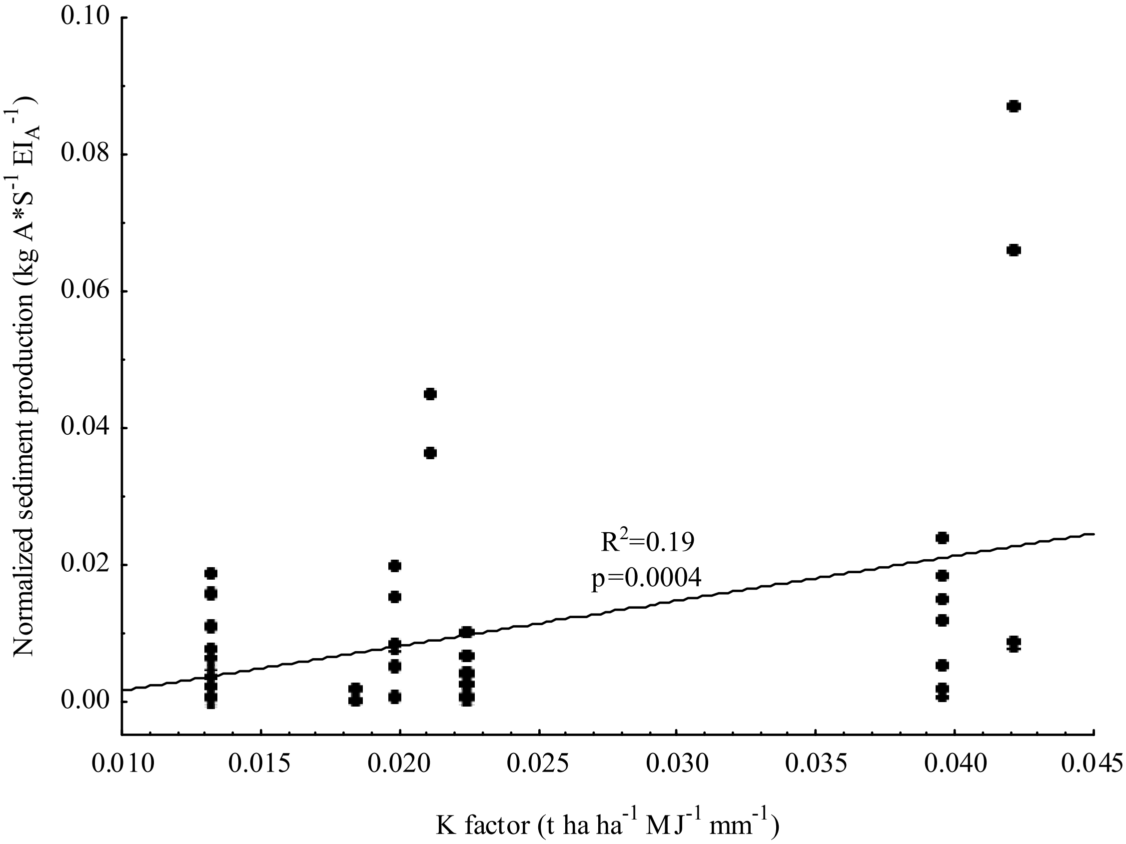

Figure 2.12. Sediment production normalized by A*S and EI_A for recently-graded native surface roads versus the published soil erodibility or K factor.

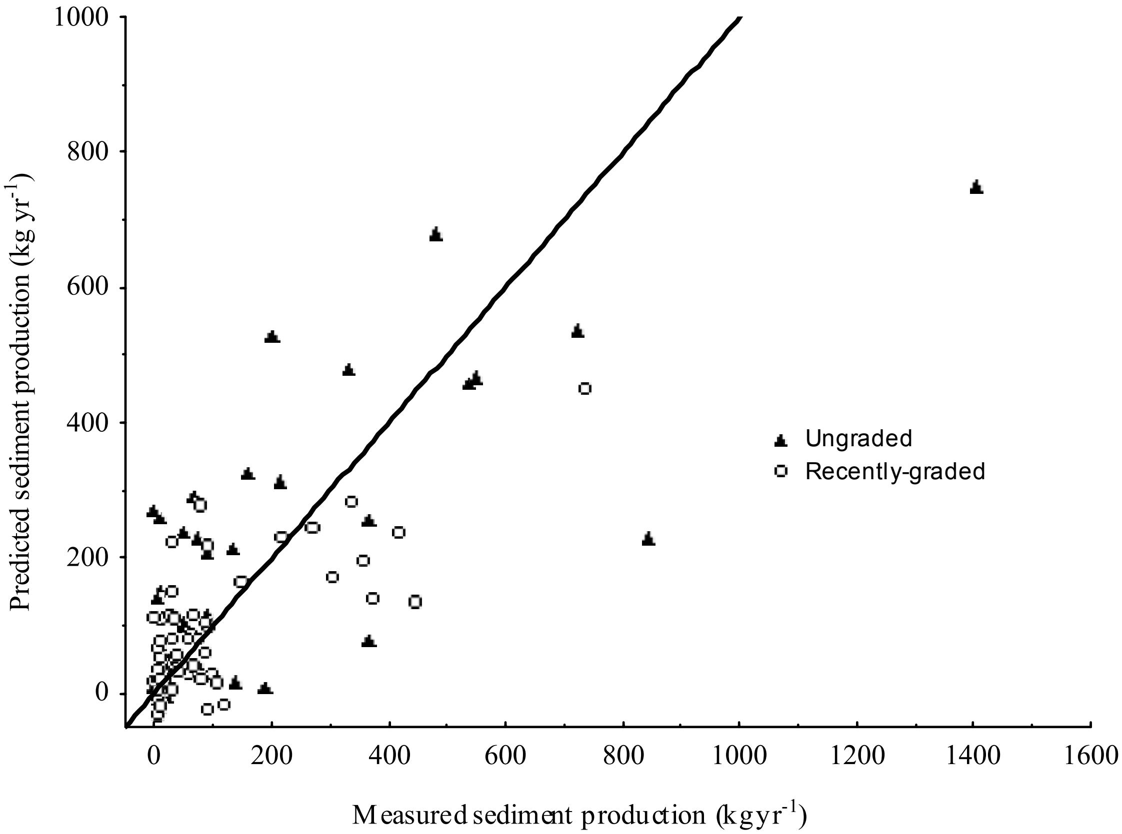

Figure 2.13. Measured versus predicted sediment production for the native surface road segments.

3.0. SEDIMENT DELIVERY FROM FOREST ROADS IN THE SIERRA NEVADA

ABSTRACT:

Sediment delivery was assessed by an intensive survey of 285 road segments along 20 km of roads in the Sierra Nevada Mountains of California. Overall, 16% of the 285 road segments and 25% of the road length were connected to the channel network. Fifty-nine percent of the connected road segments were due to stream crossings, while 35% of the connected segments resulted from road-induced gullies. Six percent of the segments were connected via sediment plumes. Sediment traveled less than 42 m below the drainage outlet for 95% of the road segments. The mean length of road-induced gullies was three times the mean length of road-induced sediment plumes. Thirty-nine percent of the variability in sediment travel distance was explained by the presence or absence of a gully below the drainage outlet, soil erodibility, estimated road traffic class, and road segment length. Gully initiation increased with road segment length, sideslope gradient, road designs that concentrated road runoff, and factors that affected the roughness and infiltration capacity below the drainage outlet. The presence or absence of gullying below a road segment was predicted with 90% accuracy by a logistic regression model. Road-induced gully volume was significantly related to the product of road length and hillslope gradient, soil erodibility, and road drainage type (R^2=0.60). The magnitude of sediment delivery from episodic gully erosion is 0.6 Mg km^{-1} yr^{-1}, compared to 1.4 Mg km^{-1} yr^{-1} of sediment delivered from road surfaces. Road sediment

delivery can be minimized by reducing the number of stream crossings in new road construction, disconnecting road drainage from stream crossings, frequently draining road segments on steep or erodible soils, and outsloping roads. An analysis of data from this and other studies shows that the proportion of road length that is connected to the stream channel network is strongly correlated with mean annual precipitation and the presence or absence of engineered drainage structures (R^2=0.92).

3.1. INTRODUCTION

Unpaved roads are chronic sediment sources in many parts of the western United States (Megahan and Kidd, 1972; Reid and Dunne, 1984; Luce and Black, 1999). Erosion from forest roads can exceed natural erosion rates by one or more orders of magnitude (Megahan and Kidd, 1972; Reid and Dunne, 1984; MacDonald et al., 2001; Ramos-Scharron and MacDonald, 2005). The resulting sediment can adversely impact aquatic resources if it is delivered to the channel network (Cederholm et al., 1981; Waters, 1995; Nelson and Booth, 2002; Suttle et al., 2004). Therefore, it is important to quantify the amount of road sediment that reaches the channel network and understand the causal mechanisms for road sediment delivery.

Several recent studies have assessed road-to-stream connectivity to help predict the hydrologic effects of roads (Wemple et al., 1996; La Marche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001), and the potential for road-related sediment to be delivered to the channel network (Croke and Mockler, 2001). The most obvious road-to-stream connection occurs at stream crossings (Wemple et al., 1996; Croke and Mockler, 2001). Connectivity also occurs when road-generated Horton overland flow (Q_{HOF}) and intercepted subsurface stormflow (Q_{ISSF}) induce gullies that extend to the stream network (Montgomery, 1994; Wemple et al., 1996; Croke and Mockler, 2001; La Marche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001). Road-related sediment also may travel downslope as sediment plumes, and some of this sediment can be delivered to the channel network (Haupt, 1959; Megahan and Ketcheson, 1996; Brake et al., 1997).

Studies in the Pacific Northwest (Montgomery, 1994; Wemple and Jones, 1996; La Marche and Lettenmaier, 2001) and southeastern Australia (Croke and Mockler, 2001) have shown that road sediment delivery is controlled by factors such as road segment length, road drainage type, hillslope gradient, hillslope curvature, and distance to the stream. However, little is known about the controlling factors for road sediment delivery in the mixed rain-snow climate in the California Sierra Nevada. The one study on road-stream connectivity in the Sierra Nevada focused on paved road networks (Montgomery, 1994), and data from different areas are needed to better understand the site-specific controls and variations in road-to-stream connectivity.

Along with high-severity wildfires, unpaved roads in the Sierra Nevada have the highest surface erosion rates in the Sierra Nevada (MacDonald et al., 2004). Data on road-to-stream connectivity are needed to predict and model the delivery of sediment from forest roads, and for assessing cumulative watershed effects. The resulting information can be used by land managers to help disconnect road sediment sources from the channel network and prioritize road maintenance and restoration efforts.

The specific objectives of this study were to: (1) characterize and quantify the pathways that control the delivery of runoff and sediment from unpaved forest roads to the channel network; (2) quantify the effect of the different site-scale factors on road-stream connectivity; (3) develop empirical models to predict road-stream connectivity; and (4) compare connectivity results from the Sierra Nevada with data from other studies.

3.2. BACKGROUND

The connectivity between roads and stream channels depends on a variety of factors. Conceptually, road-stream connectivity should increase with an increase in road and stream density due to the resultant increase in the number of stream crossings (Jones et al., 2000). In the western Cascades of Oregon, road-stream crossings accounted for almost 60% of all connected road segments (Wemple et al., 1996). The magnitude and importance of road connectivity at stream crossings will depend on the road design (e.g., outsloping), the proximity of road drainage structures on either side of the stream crossing, and all of the other factors that affect road runoff and erosion.

For the road segments that do not intersect that channel network, the travel distance of road-derived sediment depends on the amount of road-derived runoff and the factors that control the sediment transport capacity of runoff below the road drainage outlet (Megahan and Ketcheson, 1996). For roads dominated by Horton overland flow (Q_{HOF}), road length and road surface area are surrogates for the amount of runoff from a given road segment (Montgomery, 1994; Luce and Black, 1999; Chapter 2). However, for roads dominated by the interception of subsurface stormflow (Q_{ISSF}), the amount of road runoff will vary with other factors, such as the upslope drainage area and the ratio of cutslope height to soil depth (Montgomery, 1994; Wigmosta and Perkins, 2001; Wemple and Jones, 2003).

The sediment travel distance below the road segment also depends on the hillslope gradient, hillslope roughness, road drainage type, and time since construction (Haupt, 1959; Packer, 1967; Burroughs and King, 1989; Megahan and Ketcheson, 1996; Brake et al., 1997). Research in Idaho has shown that road sediment travel distance is controlled by hillslope gradient, obstructions on the hillslopes below the road drainage outlets, and road drainage type (Burroughs and King, 1989; Megahan and Ketcheson, 1996). In the Oregon Coast Range newly-constructed roads have longer sediment travel distances than older roads (Brake et al., 1997).

Several studies have evaluated the role of gullying on road sediment delivery. In western Oregon, 23% of the road drainage outlets were connected to the channel network via gullying (Wemple et al., 1996). In southeastern Australia 18% of the road sgements were connected to the stream network by gullying (Croke and Mocker, 2001). Road-induced gullies can be both a pathway for delivering road surface runoff and sediment to the channel network (Wemple et al., 1996; Croke and Mockler, 2001; LaMarche and Lettenmaier, 2001), and a source of sediment to the channel network as they develop and enlarge over time.

A gully is more likely to develop below a road drainage outlet as segment length increases (Montgomery, 1994; Wemple et al., 1996; Croke and Mockler, 2001) and hillslope gradient increases (Wemple et al., 1996). Quantitatively, the following relationship has been proposed for gully initiation:

$$L = L_t / \sin \theta \qquad (3.1)$$

where L is the critical contributing length of road necessary to initiate gullying (m), θ is the hillslope angle in degrees, and L_t is an empirical constant that represents the threshold road length (m) (Montgomery, 1994; Croke and Mockler, 2001). Gullies initiate when the product of road length and hillslope gradient exceed the L_t value.

3.3. METHODS

3.3.1. *Site Description*

The study area lies on the west slope of the Sierra Nevada mountain range in California (Figure 3.1). To the north it is bounded by the Rubicon River drainage, and to the south by the South Fork of the Cosumnes River. The primary forest type is mixed conifer, but this turns to red fir with increasing elevation (SAF, 1980). The Mediterranean-type climate means that most of the precipitation falls between November and April (USDA, 1985). Elevations range from 910 to 2000 m, and the mean annual precipitation at 1036 m is 1300 mm. The majority of the study area corresponds with the rain-on-snow climatic zone (Cobourn, 1989). Most of the road surveys were on the Eldorado National Forest, although some sites were on interspersed Sierra Pacific Industries (SPI) property.

The dominant lithologies are weathered granitic batholith, granitic glacial deposits, and volcanic (i.e., Mehrten formation) (USDA, 1985). The soils are typically coarse-textured loams. Most of the soils are over a meter thick, but the range is from 0.3 m to 1.5 m.

3.3.2. *Survey Procedures*

Twenty 1-km road transects were randomly selected and were surveyed in the summer of 2001. Each road transect was identified by randomly selecting one of the 1:24,000 USGS topographic maps in the study area, randomly selecting a section on the selected map, numbering each road in the selected section, and then randomly selecting a road using a random number generator. The roads were broken into subunits at road intersections, and one road intersection was randomly chosen as the starting point for the survey.

Each 1-km road transect was broken into road segments as defined by drainage outlets such as waterbars, rolling dips, or ditch-relief culverts, or a change in drainage direction due to ridges or stream crossings. The length of each segment was measured to the nearest decimeter with a flexible tape. The road gradient was measured at each break in slope with a clinometer, and a distance-weighted mean gradient was calculated for each segment. The width of the road tread was measured at several points and used to determine a mean width. Road segment length times the mean width yielded the road surface area for each segment.

The road segments were classified into three main drainage types: 1) outsloped segments; 2) outsloped and bermed segments; and 3) insloped segments drained by cross-relief culverts. By definition, the outsloped segments had diffuse drainage to the outside edge of the road and onto the hillslope. The outsloped and bermed roads were designed to be outsloped, but the combination of traffic and grading resulted in ruts or a berm along the outside edge that prevented runoff from leaving the road surface; drainage from these segments only occurred at a rolling dip, waterbar, or stream crossing. Segments drained by inside ditches were typically insloped, and were constructed using a cut-and-fill design with periodic relief culverts. If a segment was crowned and had an inside ditch, the road surface was divided into an outsloped and insloped portion and was counted as two road segments. In general, the outsloped roads had been more recently constructed and represented current road construction and maintenance standards, whereas the older roads were more typically insloped.

For each road segment the traffic level was qualitatively assessed as high, medium, or low. High traffic segments had evidence of recent timber hauling and typically had a thick layer of fine sediment on much of the road surface. Moderate traffic segments had evidence of frequent use by recreational traffic but no evidence of recent timber hauling. Low traffic segments had dense brush cover that prevented the use of the road by most vehicles.

Lithology, soil type, and soil depth were determined from soil survey data (USDA, 1985); lithology was field verified. The cutslope height was measured at varying intervals along the road segment length and averaged for each segment. The mean cutslope height to soil depth ratio was calculated for each segment. Hillslope gradients (m m^{-1}) below the drainage outlet and above the cutslope were measured with a clinometer. These values were averaged to obtain a mean hillslope gradient.

Each drainage outlet was assessed for signs of sediment delivery to the channel network using four connectivity classes (CC) (Wemple et al., 1996; Croke and Mockler, 2001) (Table 3.1). Road segments classified as CC1 had no signs of gullying or sediment transport below the drainage outlet, and have a very low potential for sediment delivery. Road segments classified as CC2 had gullies or sediment plumes that extended for no more than 20 m from the drainage outlet, and are considered to have a low to moderate potential for sediment delivery. Road segments identified as CC3 had gullies or sediment plumes that were at least 20 m in length, but ended more than 10 m away from the bankfull width of the nearest stream channel; these were considered to have a moderate to high potential for sediment delivery. Segments classified as CC4 intersected stream channels at stream crossings or had gullies or sediment plumes that extended to within 10 m of the bankfull edge of a stream channel. CC4 segments were classified as connected and have the highest potential for delivering sediment to the channel network (Table 3.1).

If present, the geomorphic feature below each drainage outlet that was used to indicate the sediment transport distance was categorized as either a sediment plume or a gully. Sediment plumes were defined by the presence of diffuse sediment and the absence of an actively incising channel. Gullies were defined by signs of channelized flow and incision. The length of each sediment plume and gully was measured. The top width and maximum depth of each gully was measured at 5-m intervals, and the cross-sectional area was calculated by assuming the gully had a triangular cross-section (i.e., cross-sectional area=1/2 * width * maximum depth). This area was multiplied by the length represented by each cross-section (typically 5 m) to yield a volume, and the sum of these volumes yielded the total volume for each gully.

The condition of the hillslope immediately below the drainage outlet was qualitatively assessed for the factors that may affect gully or sediment plume length. If a road segment discharged onto forest litter, the hillslope condition was categorized as "litter". If a road segment discharged runoff onto dense vegetation (e.g., brush) or large woody debris (LWD), then the hillslope condition was categorized as "energy dissipator". If a road segment discharged runoff onto compacted or disturbed soil, the hillslope condition was categorized as "disturbed".

3.3.3. Statistical Analysis

A variety of statistical methods were used to evaluate the effect of the different categorical and continuous variables on connectivity class, length of sediment plumes and gullies, gully presence or absence, and gully volume (Table 3.2). The mean values of the independent variables were compared across the discrete dependent variables, such as connectivity class or geomorphic feature, using Tukey Honestly Significant Difference (HSD) (Ott, 1993; STATISTICA, 2003). Log-normally distributed data were transformed before the Tukey HSD analysis to meet the assumptions of normality. A value of 0.1 was substituted for zero values for gully volumes, gully lengths, and sediment plume lengths in order to facilitate log transformation. Stepwise multiple regression with a selection criteria of $p<0.05$ was used to develop predictive models for gully and sediment plume lengths. Categorical variables were represented as binary variables in the model selection process. Forward stepwise logistic regression with a selection criteria of $p<0.05$ was used to predict the presence and absence of gullies below the drainage outlet. Additional logistic regression models were explored using Akaike Information Criterion (AIC) best subset model selection process (STATISTICA, 2003). All of the segments at stream crossings were excluded from the datasets used in the multiple and logistic regression analyses since the sediment plume lengths, gully lengths, and gully volumes for these segments were zero. Some gullies and sediment plumes from CC4 road segments were truncated by the stream channel, but they were left in the analysis to increase the sample size.

3.4. Results

3.4.1. Road Connectivity

The road survey covered 20 km of native surface roads and delineated 285 road segments. The mean segment length was 81 m, but lengths were highly variable as the standard deviation was 64 m and the range was from 7 m to 401 m (Table 3.3). The mean road gradient was 6%, and the range was from 0% to 17%. Hillslope gradients averaged 26% and ranged from 0% to 57%. The mean cutslope height for all road segments was 1.9 m, and values ranged up to 8.0 m. Cutslope height was significantly correlated with hillslope gradient (R^2=0.31, $p<0.0001$).

Seventy-seven percent of the road segments were outsloped but also were drained by waterbars or rolling dips. Fourteen percent were outsloped but had berms that kept the water on the road surface; these also were drained by waterbars or rolling dips. The remaining 9% of the road segments were insloped and drained by relief culverts.

Sixty-four percent of the road segments were on volcanic lithology, and the other 36% were either on weathered granitic (14%) or glacial granitic lithologies (22%). Thirty-one percent of the road segments were classified as having a high level of traffic, 48% had a moderate level of traffic, and 21% were classified as low traffic.

Sixteen percent of the road segments were connected to the stream network (Table 3.4), but these represented 25% of the total road length. Forty-nine percent of the road segments, or 38% of the total length, were categorized as CC1, meaning that there was no indication of gullying or sediment transport below the drainage outlet. Another 28% of the road segments were classified as CC2, indicating that sediment plumes and gullies extended for less than 20 m. Only 7% of the road segments had rills or sediment plumes extending more than 20 m (CC3).

Stream crossings were the dominant causal mechanism for sediment delivery to the channel network, as these accounted for 59% of the connected road segments. Another 35% of the road segments classified as CC4 were connected to the channel network by gullies. Only 6% of the road segments classified as CC4 were connected to the channel network via sediment plumes (Figure 3.2).

Connectivity class tended to increase with longer segment lengths (Figure 3.3). The mean length for the segments classified as CC1 was 63 m versus 109 m for the segments classified as CC4. The road segments classified as CC3 and CC4 were significantly longer than the segments classified as CC1 and CC2 ($p<0.0001$; Figure 3.3).

Connectivity class was strongly related to the type of road design, as approximately 90% of segments that were insloped and drained by relief culverts were classified as CC3 or CC4. In contrast, only 16% of the road segments that were drained by waterbars or rolling dips were classified as CC3 or CC4 (Figure 3.4).

3.4.2. Gully and Sediment Plume Lengths

Sediment travel distances depended on whether the geomorphic feature below the drainage outlet was a sediment plume or a gully (Figure 3.5). If the 25 segments draining directly to a stream crossing are excluded, sediment plumes were present below 29% of the road segments and the mean length was 11.8 m. The longest plume was 183 m, and this was due to road runoff being routed onto and down a skid trail. Gullies were found below just 13% of the road segments, but the mean length was nearly 37 m, or more than three times the mean sediment plume length (p=0.0001) (Figure 3.5). Ninety-five percent of the road segments had sediment plumes or gullies that were less than 42 m in length. Sediment plumes accounted for 89% of the geomorphic features present below the CC2 road segments, while gullies accounted for 67% of the geomorphic features below CC3 road segments and 83% of the geomorphic features below CC4 road segments.

The lengths of the sediment plumes increased with traffic class (Figure 3.6). The mean sediment plume length below segments with low levels of traffic was only 3.7 m, or 28% of the mean sediment plume length for roads with high or moderate levels of traffic (p=0.001).

Gully length was a power function of the soil K factor (R^2=0.27; p=0.001), indicating that gully length increased for more erodible soils. Gully length was not significantly correlated with either road segment length (p=0.07) or hillslope gradient (p=0.76).

Multivariate models could predict only 39% of the variability in gully and sediment plume lengths for the 260 road segments that were not associated with stream crossings. The best model is:

$$\mathrm{Log}_{10}(D) = 0.965 + 1.278(\log_{10} K) + 0.409(\log_{10} L) + 1.431G + 0.420T \qquad (3.2)$$

where D is the length (m) of the geomorphic feature, K is soil erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}) (p=0.004), L is road length (m) (p=0.04), G is a binary variable where 0 represents the absence of a gully and 1 indicates that a gully is present (p<0.0001), and T is a binary variable where 0 represents a low level of traffic and 1 represents a moderate to high level of traffic (p=0.001) (Figure 3.7). The adjusted R^2 for the model is 0.37, and the standard error is only 3.0 m because so many segments have either a very short or no sediment plume or gully.

3.4.3. Controls on Gully Initiation

Gullies were more likely to be present below the longer road segments, segments with relief culverts, and where the ratio of cutslope height to soil depth was greater than 1.0. The mean length of the 36 road segments with gullies was 118 m versus 64 m for the 224 segments without gullies (p<0.0001) (Figure 3.8). Approximately half of the 36 segments with gullies were insloped with relief culverts. The mean ratio of cutslope height to soil depth was 3.1 for segments with gullies; segments without gullies had a significantly lower mean ratio of 2.2 (p=0.001; Figure 3.9). A higher ratio indicates a greater likelihood of intercepting subsurface stormflow and a corresponding increase in surface runoff. Only one of the 36 road segments with a gully below the outlet had a cutslope height that was less than the soil depth.

Gully initiation was not significantly related to hillslope gradient (p=0.14), and there was not a distinct road segment area*slope or length*slope threshold (i.e., L_t) for gully initiation. However, for a given hillslope gradient a gully was more likely to occur below the longer segments (Figure 3.10). No gullies were present for road segments less than 35 m long or hillslope gradients less than 16%.

The presence or absence of gullies below road segments is best predicted by a logistic regression equation:

$$P_G = 1 / 1 + \exp [4.08 - 0.0574(L*S_H) - 3.30C + H_C] \tag{3.3}$$

where P_G is the probability of gullying; $L*S_H$ is the product of road segment length (m) and hillslope gradient (m m^{-1}); C is a binary variable with 0 representing an outsloped or bermed road segment drained by a waterbar or rolling dip and 1 representing an insloped road segment with a relief culvert; and H_C is a variable representing the condition of the hillslope 1 m below the drainage outlet. H_C is equal to zero if the drainage discharges onto forest litter, 7.1 if obstructions are present 1 m below the drainage outlet, and –2.5 if the drainage outlet discharges onto compacted soil (e.g., a skid trail or landing). If the threshold for gullying is $P_G>0.50$, the model has a 49% success rate in predicting the presence of gullies and a 96% success rate in predicting the absence of gullies, resulting in an overall model performance of 90%. If the threshold for gullying is set at $P_G>0.30$, then the model correctly predicts 63% of the gullied segments and 93% of the non-gullied segments for an overall model performance of 89%.

3.4.4. Gully Volumes

Within the study area gullies are important because they are the most common feature connecting roads to streams, and because they also can be an important source of sediment. The mean gully volume for the 36 road segments with gullies was 10.3 m^3, but the distribution was highly skewed as the median gully volume was only 3.9 m^3 and the range was from 0.01 to 153 m^3. The largest gullies are of most interest because these tended to be longer and hence more likely to reach a stream channel. In general, the cross-sectional area of gullies tended to decline as gullies progressed downslope. However, two gullies reached the inner gorge of stream channels and apparently triggered small, shallow landslides. The volume of these two slides (89.2 m^3 and 153 m^3, respectively) accounted for 54% of the total volume of sediment from gullying.

Sixty percent of the variability in gully volumes can be predicted from the following equation:

$$\text{Log10 } V = 1.88(\log 10\ K) + 1.32(\log 10\ L{*}S_H) + 0.515C + 1.503 \qquad (3.4)$$

where V is gully volume (m^3), K is soil erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}) (p=0.04), L is road length (m), S_H is hillslope gradient (m m^{-1}) ($L{*}S_H$; p=0.0004), and C is a binary variable with 0 representing the presence of a waterbar or rolling dip and 1 representing the presence of a relief culvert (p=0.04). The adjusted R^2 for the model was 0.57, and the standard error of prediction was 3.8 m^3 (Figure 3.11).

3.5. Discussion

3.5.1. *Gully and Sediment Plume Lengths*

The gully and sediment plume lengths from this study are generally less than or similar to other reported values. For newly constructed roads in the Idaho batholith, the mean length of sediment plumes was 53 m for segments with relief culverts and 12 m for segments with rock drains (Megahan and Ketcheson, 1996). The comparable mean sediment transport lengths for the mixed lithologies in this study were 29 m for segments with relief culverts and 6 m for segments drained by waterbars and rolling dips. However, the mean sediment transport lengths on weathered granitic batholith sites were 37 m for segments with relief culverts and 12 m for segments drained by waterbars and rolling dips. These latter values are very similar to the values from granitic sites in the Idaho Batholith. In central Idaho, the mean gully and sediment plume lengths below relief culverts were 20% shorter on metasedimentary lithologies than volcanic and granitic lithologies (Burroughs and King, 1989). The overall mean sediment travel distance of 8.7 m in this study is very similar to the mean sediment transport distances on sandstone lithology in the Oregon Coast Range of 5.1 m for old roads and 9.3 m for new roads (Brake et al., 1997).

The empirical model developed to predict gully and sediment plume length uses four variables (Eq. 3.2), and each of these variables has a physical basis. Gully or sediment plume length increases with increasing road segment length because the latter is a surrogate for the amount of road surface runoff. An increase in runoff will increase both the amount of eroded sediment and the downslope transport capacity (Luce and Black, 1999). The binary variable for the presence or absence of a gully implicitly recognizes that gullies have more concentrated runoff and a greater travel distance than the more diffuse flow associated with sediment plumes. The greater length with an increase in the K factor reflects the increase in soil erodibility with decreasing particle size and decreasing soil permeability (Lal and Elliot, 1994). Silts and fine sands are more easily detached and transported than larger particles, and a lower permeability will reduce downslope infiltration and thereby increase the travel distance.

Higher traffic levels were associated with an increase in sediment plume length but not an increase in gully length. An increase in traffic on unpaved roads increases the supply of erodible sediment that can be transported below the drainage outlet (Ziegler et al., 2001a; Ziegler et al., 2001b). In this study sediment plume lengths were significantly shorter for roads that were partly overgrown and characterized as having a low level of traffic. The vegetation on these low traffic segments is presumably reducing the amount of both runoff and erosion, and the mean plume length of 3.7 m for the low traffic segments is consistent with this explanation.

3.5.2. Gully Initiation

Gully initiation was more likely with longer road lengths, steeper hillslope gradients, insloped roads, and smoother hillslopes (Eq. 3.3). It has already been shown that longer road segment lengths are a surrogate for increased runoff and flow depths (Luce and Black, 1999). An increase in runoff and hillslope gradient will increase shear stress, and gully initiation is more likely as shear stress increases (Montgomery, 1994). The inclusion of $L*S_H$ in equation 3.3 is consistent with results from the western Cascades in Oregon, where $L*S_H$ was a significant variable in a logistic regression model developed to predict gully initiation below road drainage outlets (Wemple et al., 1996).

The type of road drainage is an important control on gully initiation, as much shorter segment lengths are needed to initiate gullies on insloped roads drained by relief culverts than for outsloped or bermed roads drained by waterbars or rolling dips. Using Equation 3.3 and assuming the mean segment length of 81 m and the mean hillslope gradient of 26%, the probability for gullying increases from 0.05 to 0.61 when a road segment is insloped and drained by a relief culvert as opposed to outsloped and waterbarred. The higher likelihood of gullying can be attributed to the more highly concentrated flow at the outlet of the relief culvert. In southeastern Australia the majority of gullies also were also associated with relief culverts as compared to other types of drainage outlets (Croke and Mockler, 2001). Figures 3.12a and 3.12b show the critical road segment length needed to have a 50% probability of gully initiation for a given hillslope gradient and hillslope condition for two drainage types.

The condition of the hillslope below the drainage outlet is important because this controls other factors, such as surface roughness and infiltration capacity, that directly affect the likelihood of gullying. Gully initiation was least likely when natural energy dissipating obstructions such as brush or LWD were present 1 m below the drainage outlet (Figure 3.12). Gully initiation was most likely when road runoff was discharged onto compacted or disturbed soils, such as skid trails. According to equation 3.3, an outsloped road with a mean length of 81 m and the mean hillslope gradient of 26% has a zero probability of gullying when an energy dissipating obstruction is below the drainage outlet, a 5% probability when the segment discharges onto forest litter, and a 42% probability of gullying if the segment discharges onto compacted soil. The corresponding probabilities for a comparable insloped road are zero, 61%, and 95%, respectively. This indicates that gully initiation below insloped roads with relief culverts is particularly sensitive to the condition of the hillslope below the drainage outlet (Figure 3.12b), and that the placement of energy dissipators below relief culverts are an effective best management practice to prevent gully erosion.

Upslope soil depth was not included in the model to predict gully initiation because it had a p-value of 0.11, but in some situations soil depth can be an important factor in gully initiation. For midslope roads, gullying is more likely when the cutslope height exceeds soil depth, as this will increase the amount of Q_{ISSF} (Wigmosta and Perkins, 2001; Ziegler et al., 2001c; Wemple and Jones, 2003). Soil depth was included when the Akaike Information Criterion (AIC) model selection process was used instead of stepwise regression. If soil depth is added to the predictive model, the success rate of predicting the presence of gullies increased from 48% to 54% when using a P_G of 0.50. Soil depth is much less likely to be important for ridgetop roads or valley bottom roads with small cutslopes, and this is probably why soil depth was not included in the overall model.

3.5.3. Gully Volumes

Gully volumes increased with longer road segment lengths, steeper hillslopes, higher K factors, and the presence of relief culverts (Eq. 3.4). As noted earlier, longer segments increase the amount of road runoff and steeper hillslope gradients increase shear stress and gully erosion (Mongtomery, 1994). Road drainage type determines whether the runoff is partially dispersed or concentrated at the drainage outlet, and the flow velocity. The logistic regression equation used to predict the presence or absence of gullies also explains 29% of the variability in log-transformed gully volumes (p=0.0007). This shows that the road segments with the highest probability for gullying also should have the highest gully volumes.

The connectivity data and the predictive equations can be used to calculate the amount of sediment being delivered from road-induced gullying versus the amount of sediment being delivered from road surfaces. The total volume of sediment delivered to the channel network by gully erosion was 355 m^3, or 18 m^3 per km of road. If a bulk density of 1.6 Mg m^3 is assumed, the sediment delivery rate from road-induced gullies is 29 Mg per kilometer of road length. In the western Cascades of Oregon road-induced gullies were associated with flood events with a 30- to 100-year recurrence interval (Wemple et al., 2001). If gullies are assumed to form in response to storms with a recurrence interval of 50 years, the mean annual sediment delivery rate from gullies would be 0.6 Mg km^{-1} yr^{-1}.

This value can be compared to the amount of sediment being produced and delivered from the road surface. The prediction equation for road surface erosion from native surface roads is:

$$SP_{ns} = -329 + 3.56\,(A*S) + 0.542\,EI_A + 0.389\,(A*G) \qquad (2.7)$$

where SP_{ns} is sediment production in kilograms per year, A*S is the product of road area and road slope (m^2), EI_A is annual erosivity (MJ mm ha^{-1} hr^{-1}), and A*G is the product of road area and a binary variable (G) with 1 representing a recently-graded road and 0 representing an ungraded road (Chapter 2). This equation was used to predict the amount of sediment being produced from each road segment that was connected by a stream crossing, gully or sediment plume. The calculations assumed a mean annual erosivity of 1360 MJ mm ha^{-1} hr^{-1} (Renard et al., 1997), that none of the roads had been recently graded, and that all of the sediment from a connected road segment was reaching the stream channel. The resulting sediment delivery rate for road surface erosion was 1.4 Mg km^{-1} yr^{-1}, or 2.3 times the estimated gully erosion rate of 0.6 Mg km^{-1} yr^{-1}.

The validity of this comparison depends on the assumptions regarding the storm recurrence interval for gully formation, the mean annual erosivity, the frequency of road maintenance activities, the percent of sediment delivered from the connected segment and the gully, and the accuracy of the sediment prediction model. Road-induced gully erosion may be a larger contributor of sediment to the channel network if gullies form during storms with a shorter recurrence interval. For example, the amount of sediment from gullies would double if gully erosion results from storms with a recurrence interval of 25 years rather than 50 years. The amount of sediment from road surfaces is sensitive to the annual erosivity and the presence or absence of grading. For example, assuming an EI_A of 2000 MJ mm ha^{-1} hr^{-1} would increase sediment delivery from road surfaces from 1.4 to 2.2 Mg km^{-1} yr^{-1}. If all roads are recently-graded, the sediment delivery from road surfaces would increase by 50% to 2.1 Mg km^{-1} yr^{-1}. The key point is that large amounts of sediment can be produced and delivered from road-induced gullies as well as road surface erosion.

3.5.4. *Connectivity*

The road survey showed that 16% percent of the road segments and 25% of the total road length was connected to the channel network. These values are low relative to most other studies. In southeastern Australia, 38% of the road length was connected to the streams in an area with similar Mediterranean climate (Croke and Mockler, 2001). In northwestern California 32% of the road segments were connected to the channel network (Raines, 1991). However, in the drier Front Range of Colorado, 18% of the total road length was connected to the channel network (Libohova, 2003).

An analysis of the data from these and other studies suggests that the percentage of unpaved roads that are connected to the stream network increases with mean annual precipitation and decreases with the presence of engineered road drainage structures such as waterbars, rolling dips, and relief culverts (Reid and Dunne, 1984; Raines, 1991; Wemple et al., 1996; Bowling and Lettenmaier, 2001; Croke and Mockler, 2001; Ziegler et al., 2000; Libohova, 2004; Sidle et al., 2004; A. Ziegler, personal comm., 2003). An empirical prediction equation using these two factors can explain 92% of the variability in road connectivity:

$$C = 12.9 + 0.016\ P + 39.5\ M \tag{3.5}$$

where C is either the percent of road length or percent of road segments that are connected to the channel network, P is the mean annual precipitation (mm), and M is a binary variable with 0 representing roads with engineered drainage structures, and 1 representing roads without engineered drainage structures ($p<0.0001$) (Figure 3.13). Mean annual precipitation explains 41% of the variability in connectivity ($p=0.03$) for the entire dataset, and 84% of the variability in connectivity for roads with engineered drainage structures ($p=0.001$). The standard error of the estimate is 8.2%. To develop this equation it was assumed that the percent of connected segments was equivalent to the percent of the connected road length. Although this assumption is not strictly true because the longer segments are more likely to be connected, it was necessary in order to pool the data collected using each approach.

There are several reasons why mean annual precipitation is the dominant control on road-stream connectivity. Increasing precipitation tends to increase drainage density (Gregory, 1976; Montgomery and Dietrich, 1988), and an increase in drainage density will increase the number of stream crossings. An increase in precipitation also will increase the amount of road runoff, which will increase the number and length of road-induced gullies (Montgomery, 1994; Luce and Black, 1999; Croke and Mockler, 2001).

The binary variable reflects the ability of road drainage structures to disconnect road segments from the channel network. Frequent drainage structures reduce the amount of runoff available for gully initiation and the downslope transport of road-related sediment (Montgomery, 1994; Croke and Mockler, 2001). The careful placement of drainage structures also can help reduce the amount of road drainage that reaches the stream at stream crossings. The coefficient for the dummy variable in Eq. 3.5 indicates that engineered drainage structures will decrease the connectivity by about 40% relative to roads without engineered drainage structures.

3.5.5. Management Implications

The data in Figure 3.13 indicate that road connectivity is lower in the study area than in wetter areas such as the Pacific Northwest, but that sediment is being delivered to the streams from 25% of the road network. A study of 28 pool-riffle reaches in the study area found a positive correlation between estimated road sediment production and residual pool infilling (R^2=0.14; p=0.02) (MacDonald et al., 2003). Relatively small increases in fine sediment can adversely affect fish by decreasing the growth and survival of juvenile fish, and decreasing the availability of invertebrate prey species (Suttle et al., 2004). The response of juvenile fish and invertebrates to fine sediment loading is linear, suggesting that any increase in fine sediment will have a detrimental effect (Suttle et al., 2004).

The results of this study have important management implications for reducing road sediment delivery. First, most roads are connected at stream crossings, so the number of stream crossings should be minimized when designing and constructing unpaved roads. Second, the production and delivery of road sediment to stream crossings can be reduced by rocking the approaches to stream crossings (Chapter 2) and minimizing the length of the road segments that drain directly to the crossing (Eq. 2.7).

Third, the size and length of sediment plumes and gullies can be minimized by reducing road runoff and reducing traffic. This will reduce the amount of sediment that is delivered and the amount of sediment that is generated by gully erosion. The amount of runoff from a road segment can be reduced by shortening the road segment length, outsloping the road surface, and minimizing cutslope heights on shallow soils. Gully initiation below road segments can be minimized by avoiding sensitive sites as identified by hillslope gradient, soil depth, and hillslope condition. Gully initiation also can be minimized by improved road designs in terms of decreasing the spacing of drainage structures, changing road drainage type, and minimizing cutslope height. The road drainage guidelines in Figure 3.12 can be used to minimize the risk of gullying below a road drainage outlet.

Fourth, sediment delivery from gully erosion can be minimized by improved road drainage. Gully volumes and travel distance can be reduced by shortening segment lengths and outsloping the road surface. Managers should avoid insloping road segments on erosive soils and steeper hillslopes. Finally, 95% of road segments transported sediment less than 42 m from the drainage outlet. If roads can be placed or relocated at least 40 m from stream channels, sediment delivery via sediment plumes and gullies should be minimized.

3.6. Conclusions

This study measured the extent to which unpaved forest roads in the Sierra Nevada of California are connected to the stream channel network. A detailed survey along 20 km of unpaved roads identified 285 road segments. Sixteen percent of the 285 road segments and 25% of the road network length were connected to the channel network. Fifty-nine percent of the connected road segments were due to stream crossings, while 35% were connected by road-induced gullies. Only 6% of road segments were connected via sediment plumes.

The mean gully length was 37 m. or roughly 3 times larger than the mean sediment plume length, and the longest gully was 95 m. Multivariate analysis indicated that the length of sediment plumes and gullies below road drainage outlets was controlled by the presence or absence of gullies, soil erodibility, traffic level, and road segment length (R^2=0.39; $p<0.0001$). Road-induced gullies were more frequent on insloped roads drained by relief culverts, longer road segments on steeper slopes, and drainage outlets discharging onto hillslopes with relatively low surface roughness or low infiltration due to compaction. A logistic regression model using these factors had a 90% success rate in distinguishing between gullied and ungullied segments. Gully volume was significantly related to the product of road segment length and hillslope gradient, soil erodibility, and road drainage type (R^2=0.60; $p<0.0001$). Gully volumes were significantly higher below relief culverts than for waterbars or rolling dips. The amount of sediment delivered from road-induced gully erosion was 43% of the amount of sediment delivered from road surfaces. Road sediment delivery can be minimized by reducing the number of stream crossings, outsloping and frequently draining roads on erosive soils and steep hillslopes, and placing new roads further from stream channels.

An analysis of data from 10 studies shows that road-stream connectivity is strongly controlled by mean annual precipitation and the presence or absence of engineered drainage structures (R^2=0.92; p<0.0001). The absence of engineered drainage structures will increase connectivity by approximately 40%. The findings of this and other studies indicate that maintaining and improving road drainage is an effective means to reduce road sediment delivery.

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3.7. TABLES AND FIGURES

Connectivity class	Geomorphic criteria	Potential for sediment delivery
1	No signs of gullying or sediment transport below drainage outlet	Low
2	Gullies or sediment plumes <20 m in length	Low/moderate
3	Gullies or sediment plumes >20 m in length, but more than 10 m from stream channel	Moderate/high
4	Gullies or sediment plumes to within 10 m of a stream channel	High

Table 3.1. Road connectivity classes and their estimated potential for sediment delivery.

Dependent variables	Independent variables
Connectivity class (CC)	Road segment gradient (S)
Geomorphic feature (gully or sediment plume)	Road surface area (A)
Sediment travel distance below outlet (m)	Road length (L)
Gully presence or absence	Hillslope gradient (SH)
Gully volume	Cutslope height
	Soil series
	Lithology
	Soil depth
	Soil erodibility (K factor)
	Road drainage type (outsloped, bermed, or insloped with relief culvert)
	Geomorphic feature (gully or sediment plume)
	Hillslope condition

Table 3.2. List of dependent and independent variables used in pairwise comparisons, multiple regression, and logistic regression.

Variable	Mean	Range		Std. dev.
		Minimum	Maximum	
Segment length (m)	76	7	401	64
Segment area (m^2)	563	43	5260	587
Segment gradient ($m\ m^{-1}$)	0.06	0	0.17	0.03
Cutslope height (m)	1.9	0.2	8.0	1.1
Hillslope gradient ($m\ m^{-1}$)	0.26	0.01	0.57	0.11
K factor ($t\ ha\ h\ ha^{-1}\ MJ^{-1}\ mm^{-1}$)	0.017	0.013	0.032	0.017
Soil depth (m)	1.0	0.30	1.6	0.40

Table 3.3. Mean, range, and standard deviation of the independent variables used to characterize each segment.

Connectivity class	Number of segments	Percent of total segments	Road length (km)	Percent of total length
1	138	48.4	8.11	37.7
2	81	28.4	5.62	26.1
3	20	7.0	2.25	10.5
4	46	16.2	5.55	25.7
Total:	285	100	21.53	100

Table 3.4. Number of road segments and road length by connectivity class.

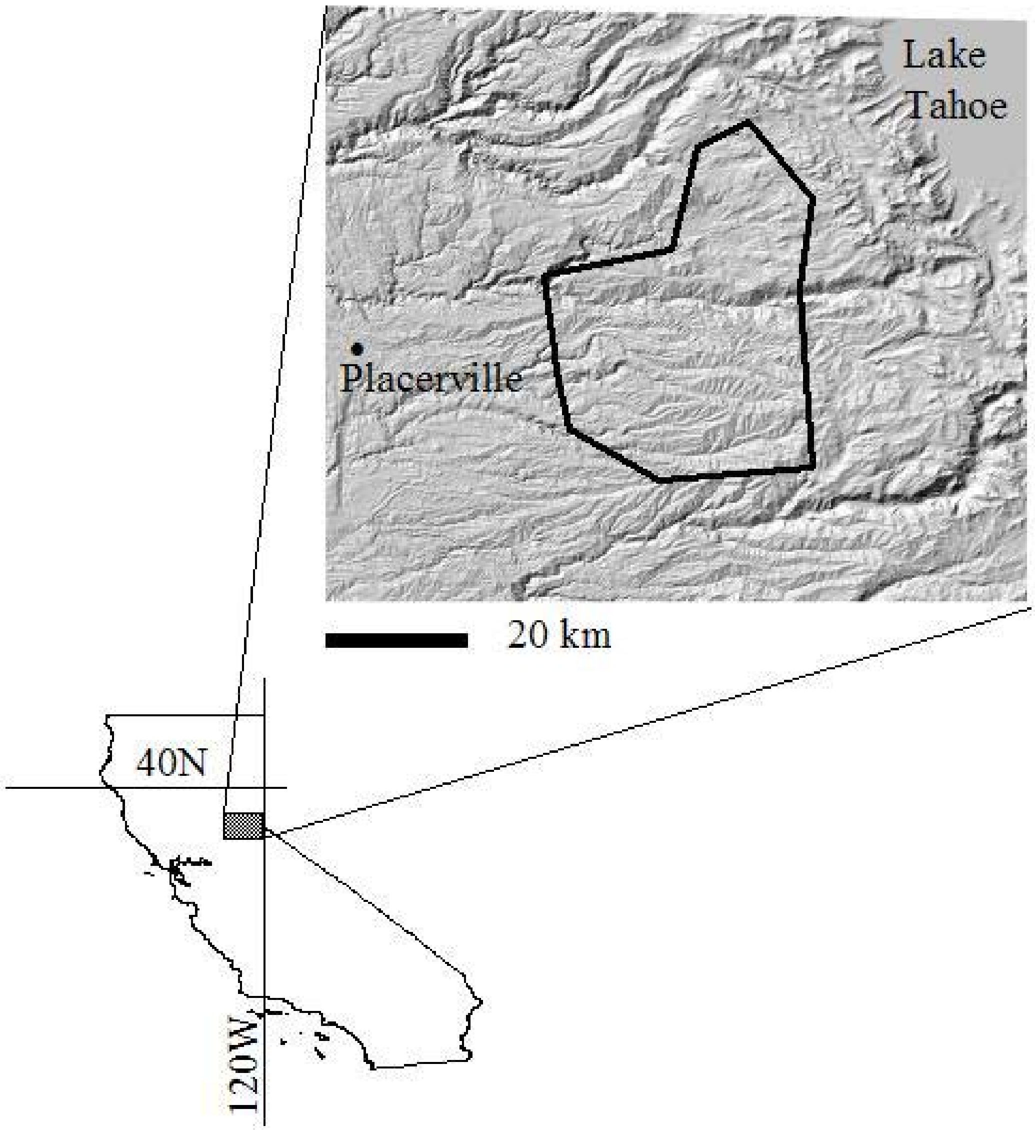

Figure 3.1. Map of the study area.

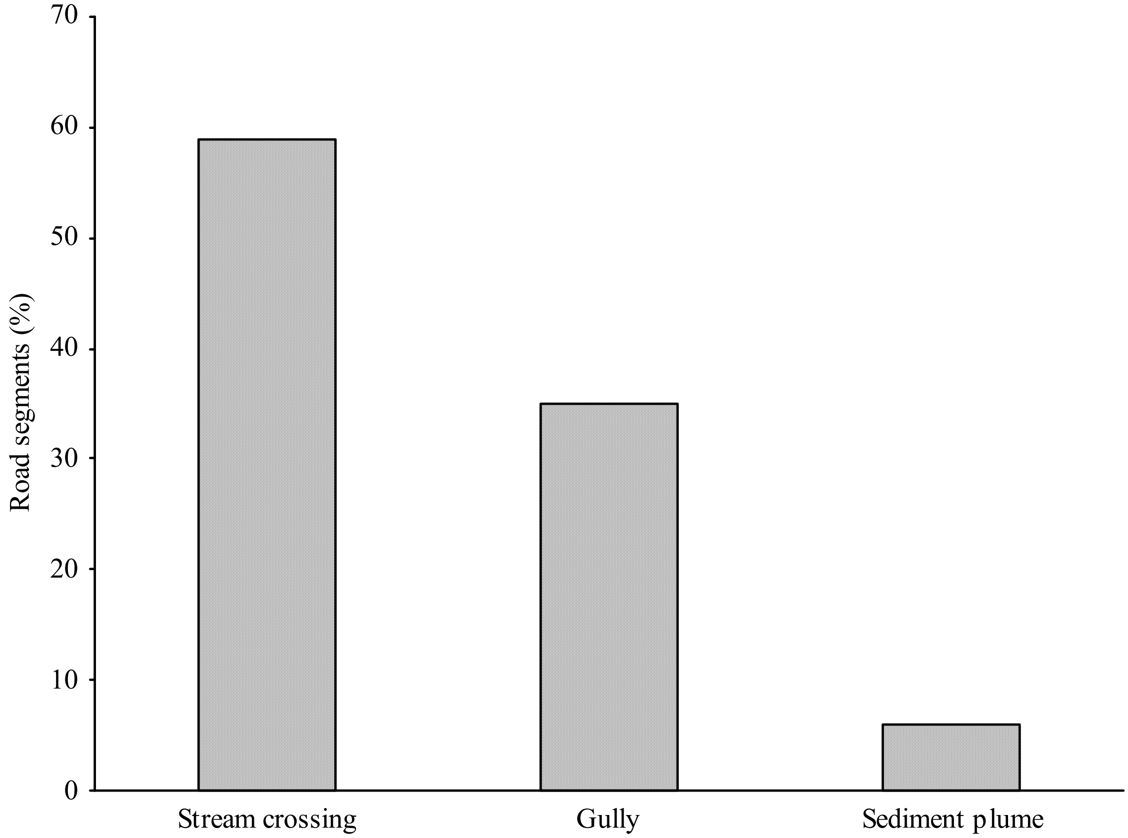

Figure 3.2. Percent of road segments connected to the channel network by causal mechanism (n=46).

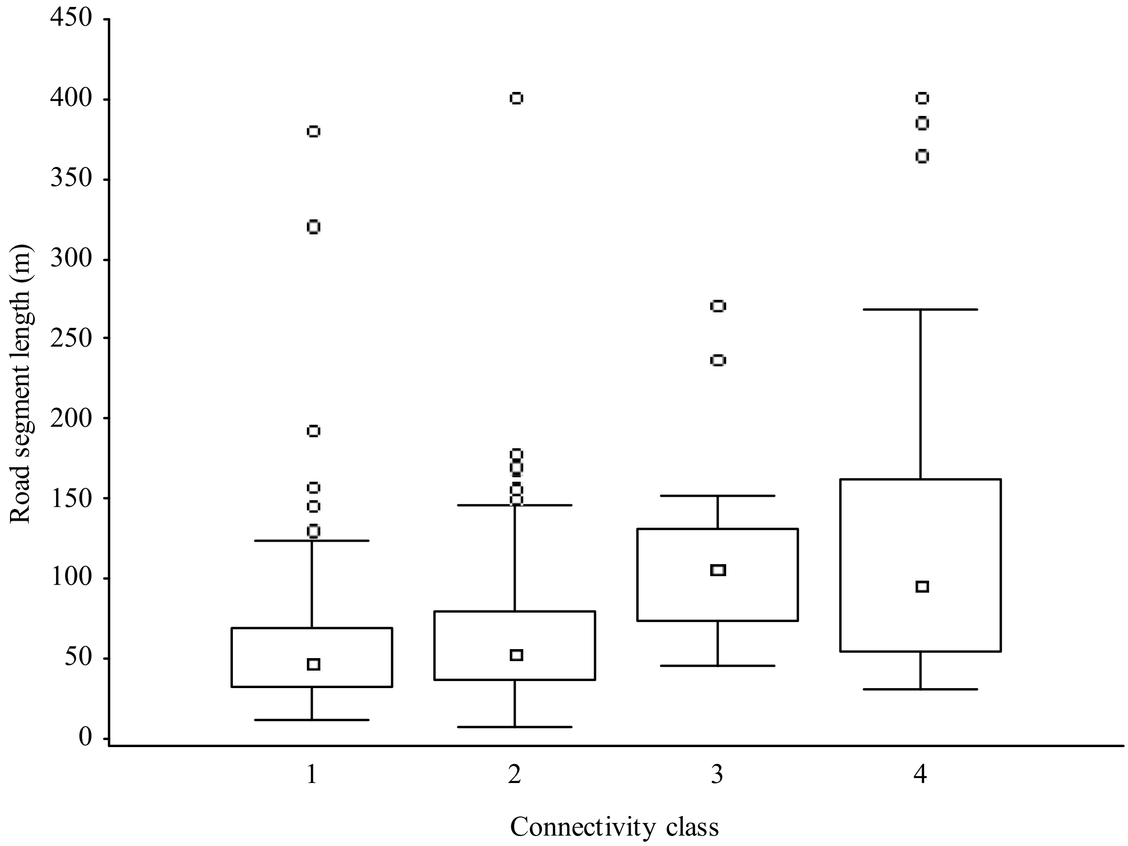

Figure 3.3. Road segment length by connectivity class. The small squares are the median segment length, the boxes indicate the 25th and 75th percentiles, the bars show the 95% confidence interval, and the open circles represent outliers.

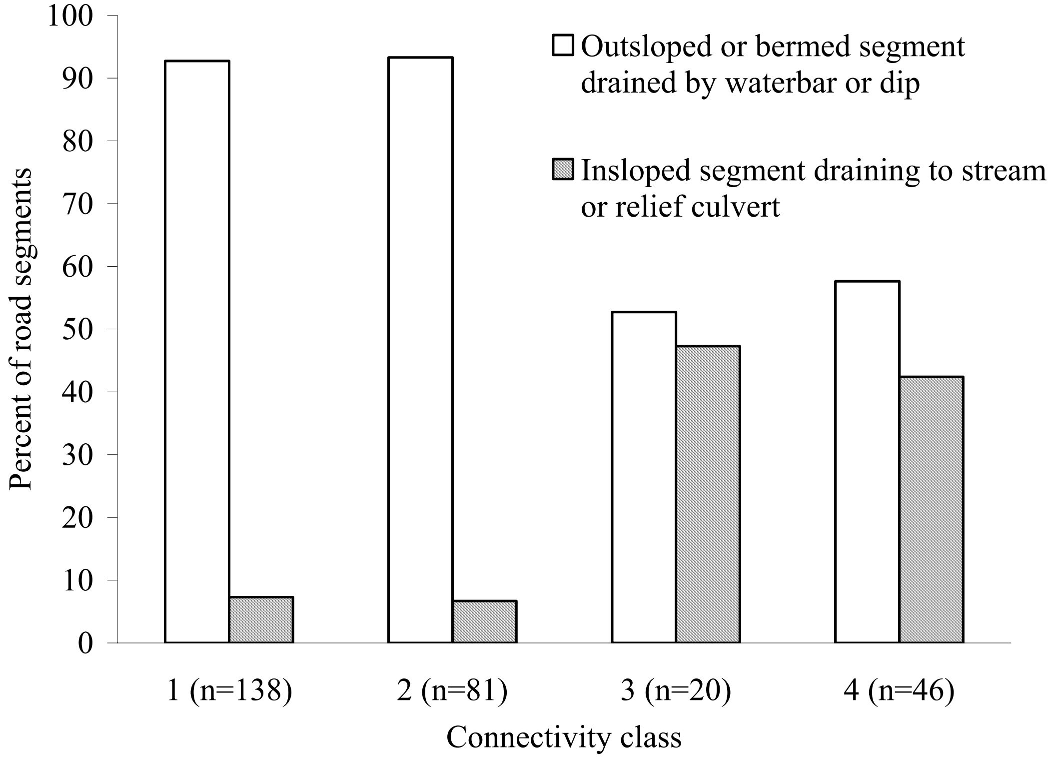

Figure 3.4. Percent of road segments by road drainage type for each connectivity class.

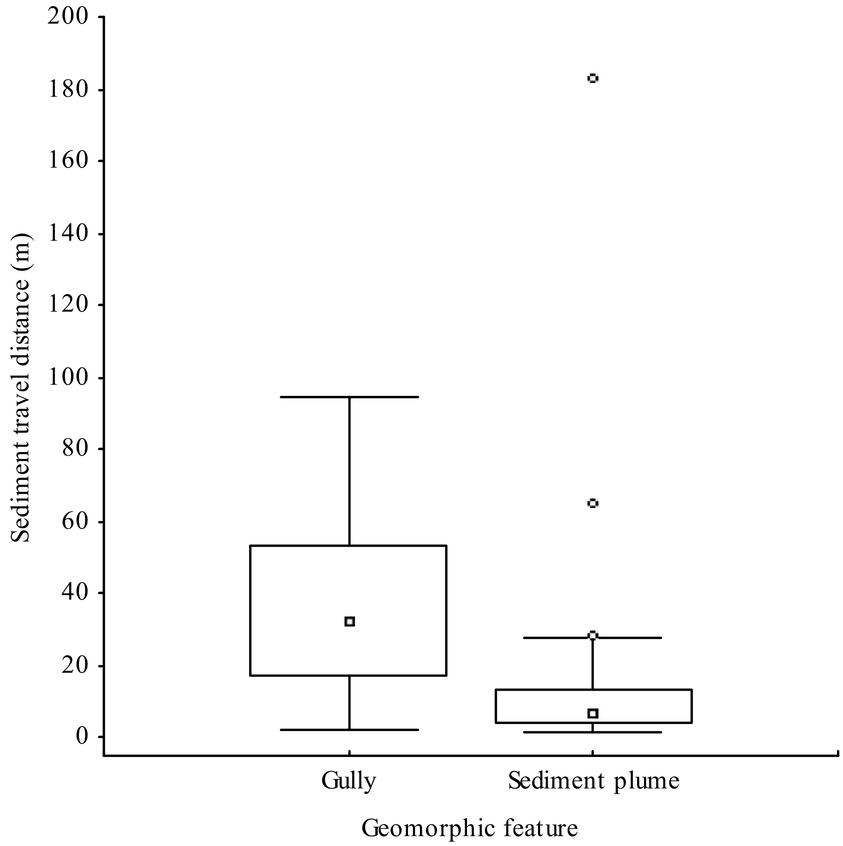

Figure 3.5. Lengths of gullies and sediment plumes for the segments classified as CC2, CC3, and CC4. The small squares are the median length, the boxes indicate the 25th and 75th percentiles, the bars show the 95% confidence interval, and the open circles represent outliers.

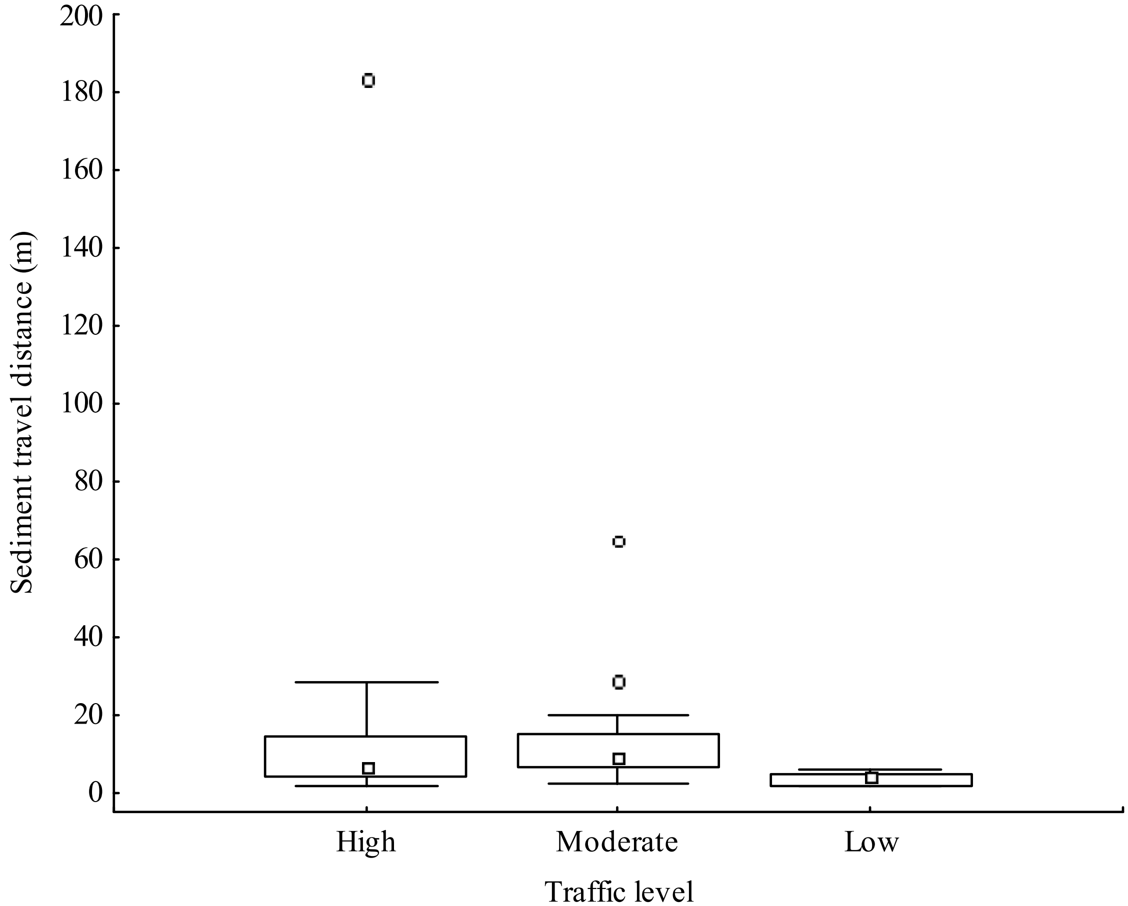

Figure 3.6. Lengths of sediment plumes by traffic level. The small squares are the median segment length, the boxes indicate the 25th and 75th percentiles, the bars show the 95% confidence interval, and the open circles represent outliers.

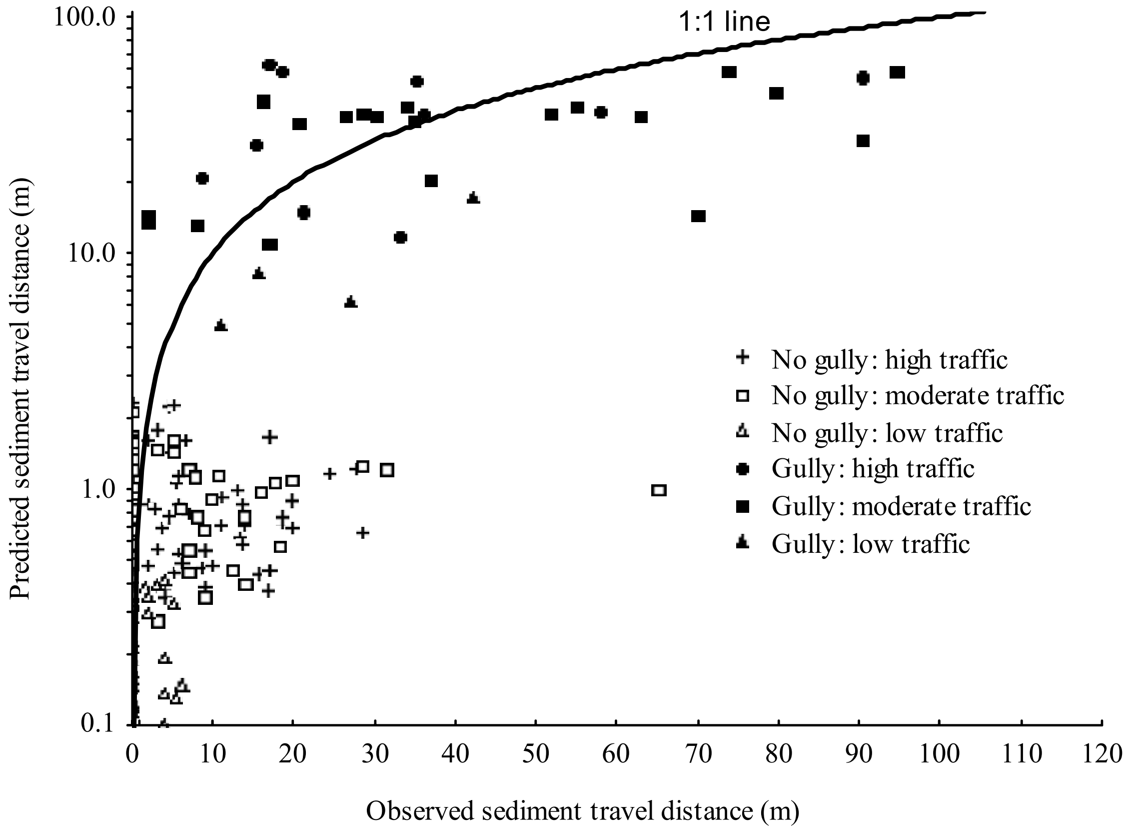

Figure 3.7. Predicted gully and plume lengths versus observed values by geomorphic feature and traffic class.

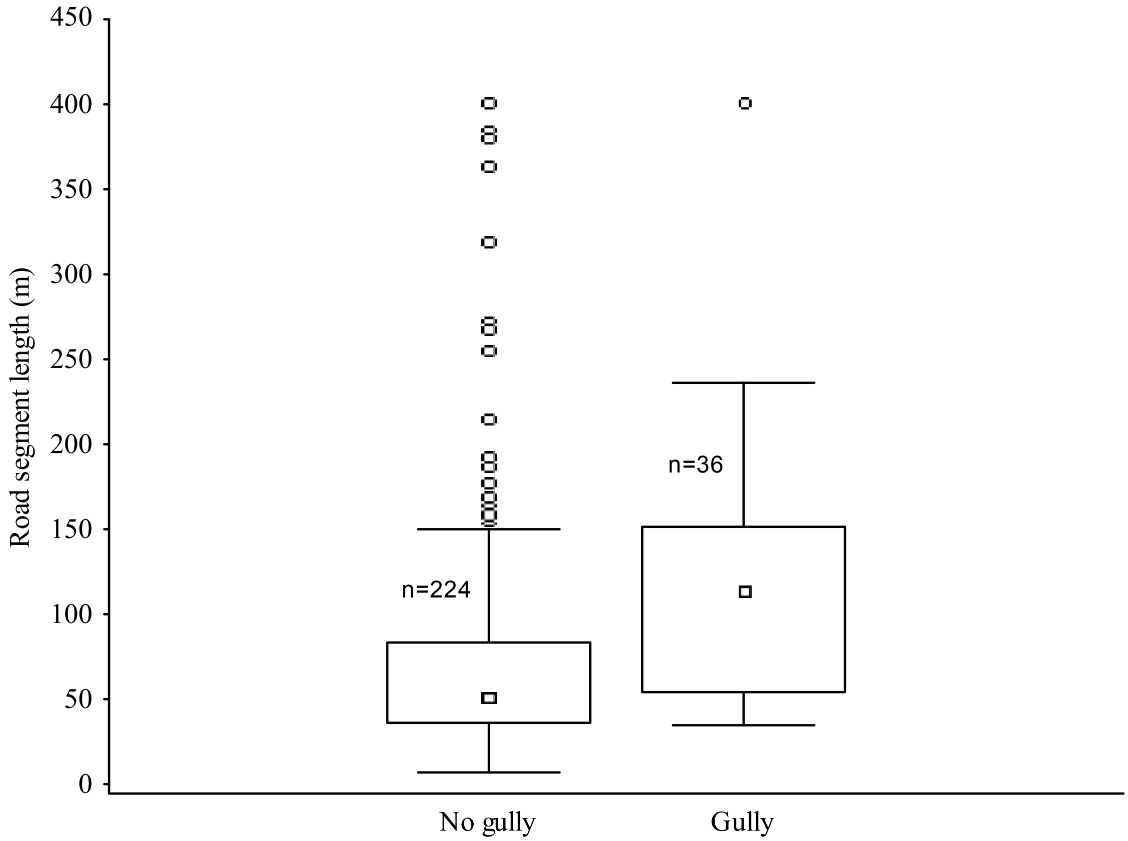

Figure 3.8. Road segment length for outlets with and without gullies. The small squares represent the median road segment length, the boxes indicate the 25th and 75th percentiles, error bars represent the 95% confidence intervals, and the open circles represent outliers.

Figure 3.9. Ratio of cutslope height to soil depth for segments with and without gullies below the drainage outlet. The small squares represent the median ratio, the boxes indicate the 25th and 75th percentiles, error bars represent the 95% confidence intervals, and the open circles represent outliers.

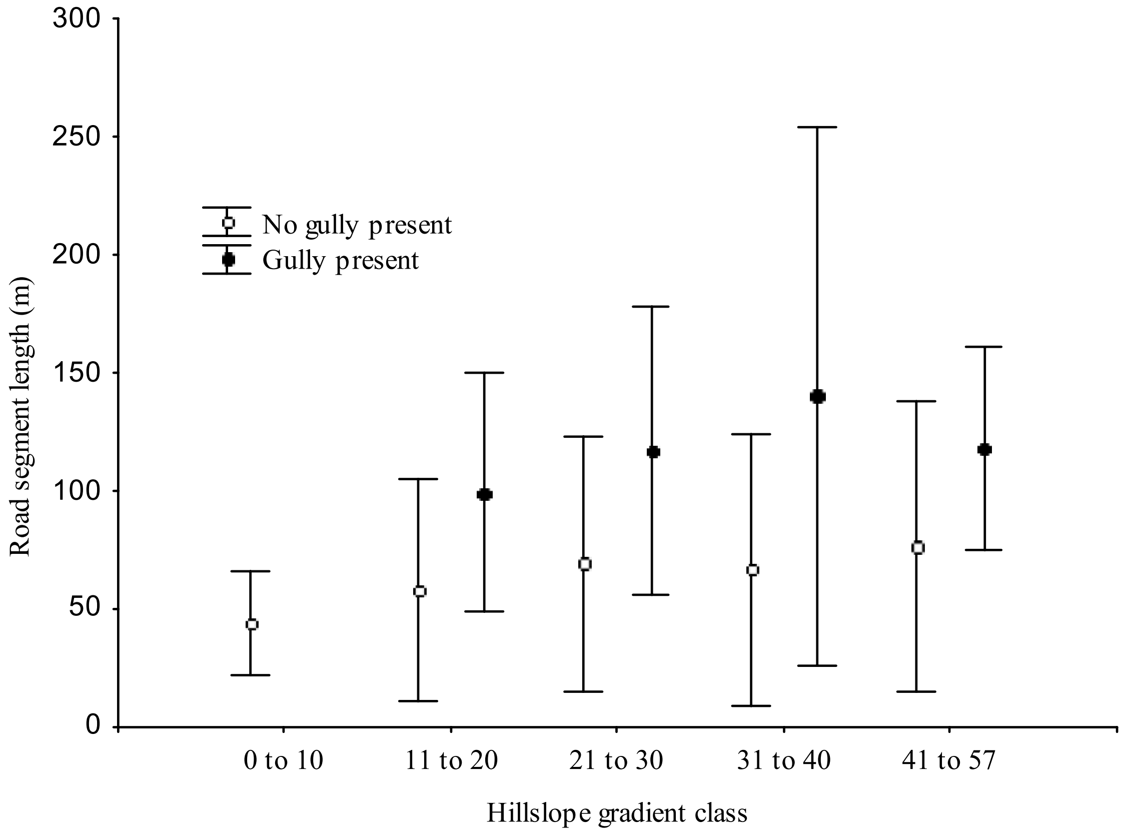

Figure 3.10. Mean road segment length for gullied and ungullied road segments by hillslope gradient class. Bars represent one standard deviation.

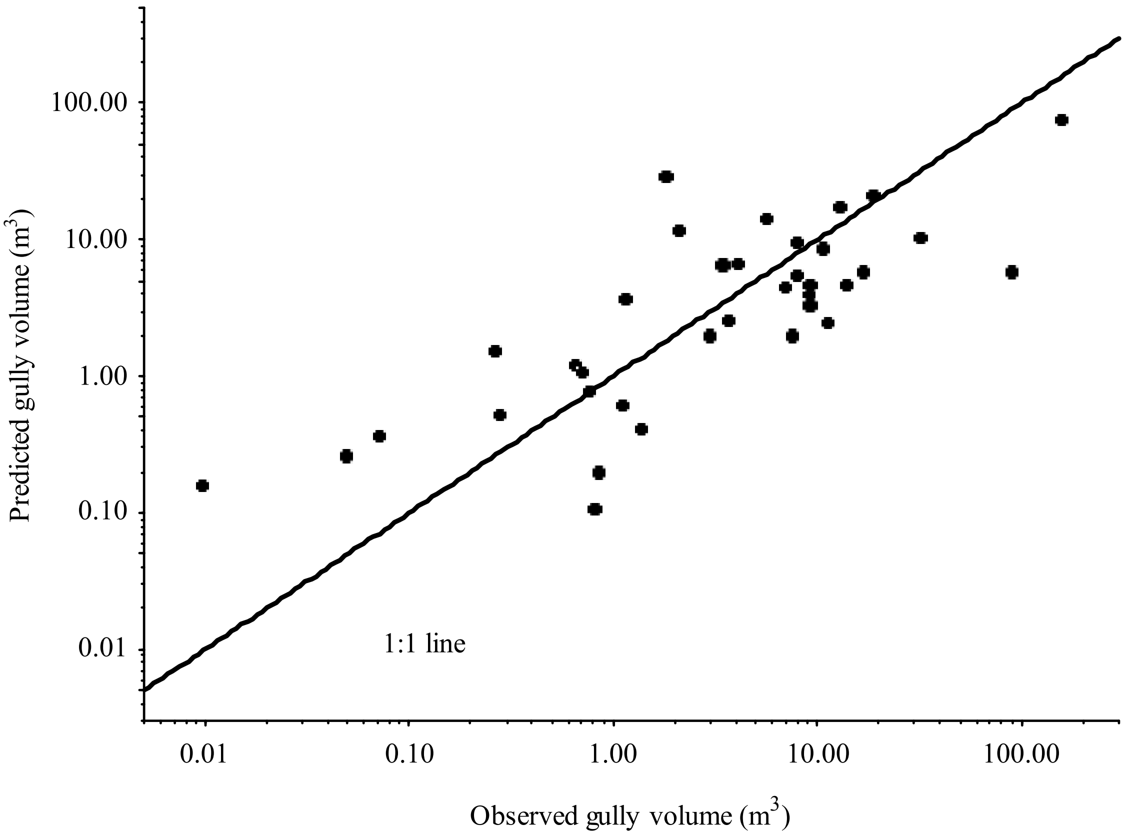

Figure 3.11. Predicted versus observed gully volumes.

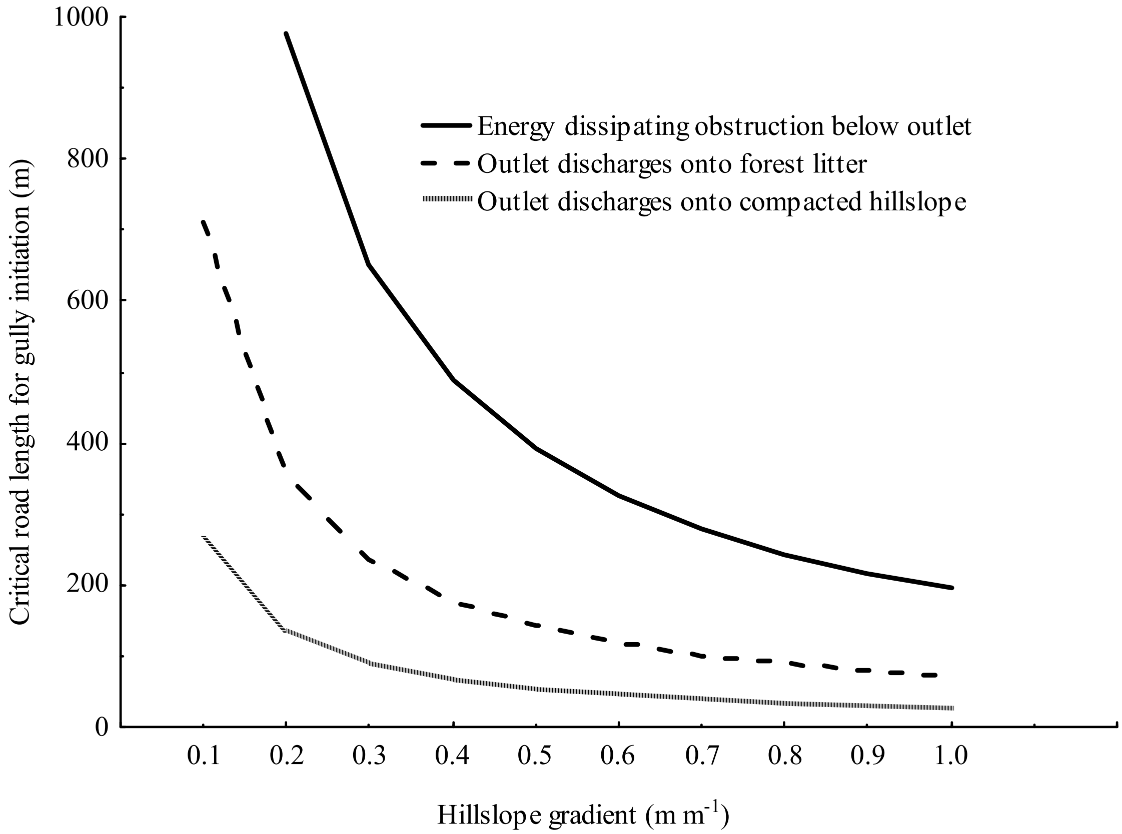

Figure 3.12a. Predicted road segment length thresholds (L_t) for avoiding gully initiation below outsloped roads drained by waterbars and rolling dips. Each curve represents a 50% probability of gullying for a different hillslope condition across a range of hillslope gradients.

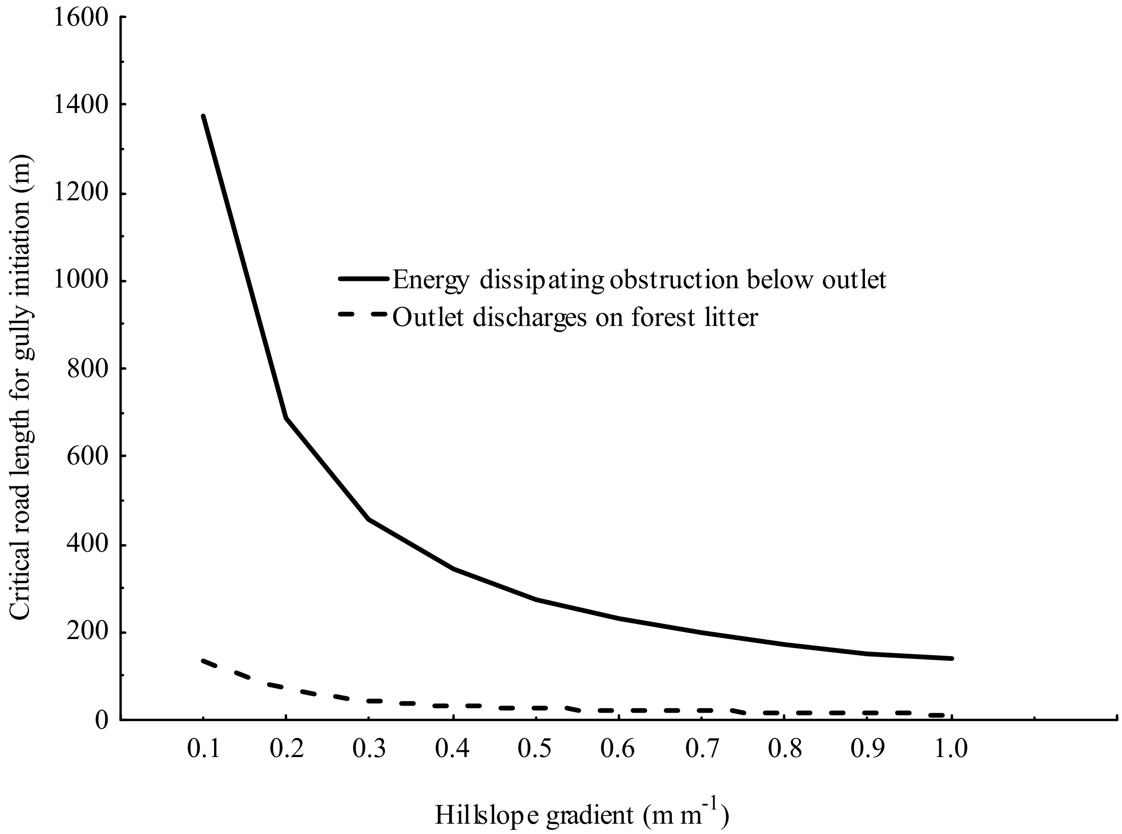

Figure 3.12b. Predicted road segment length thresholds (L_t) for avoiding gully initiation below insloped roads drained by relief culverts. The two curves represent a 50% probability of gullying for two different hillslope conditions across a range of hillslope gradients. No curve is shown for compacted hillslopes as all relief culverts that discharge onto compacted hillslopes are predicted to have gullies.

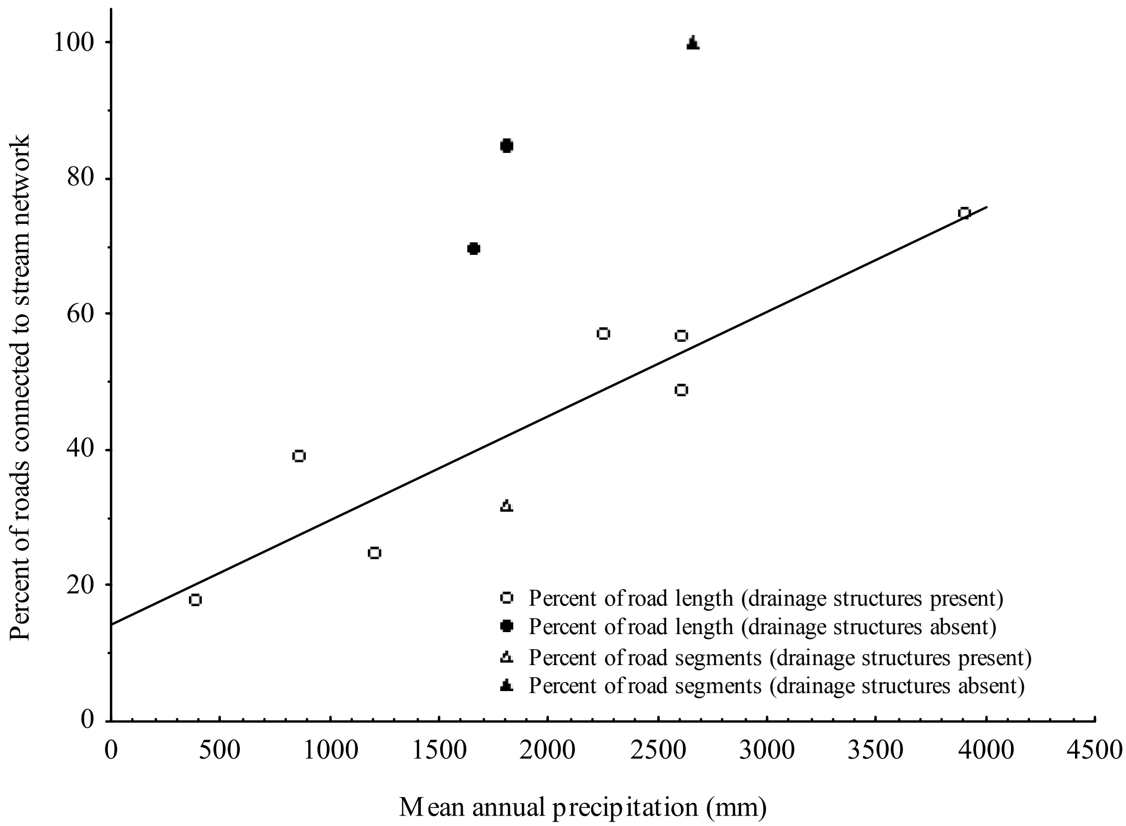

Figure 3.13. Percent of roads connected to the stream network versus mean annual precipitation for roads with and without engineered drainage structures. Regression line is for roads with engineered drainage structures.

4.0. Conclusions

The two studies provide a unique and quantitative understanding of sediment production and sediment delivery from unpaved roads in the Sierra Nevada of California. Sediment production rates varied greatly between years and between road segments. Most of the interannual variability in sediment production rates can be attributed to differences in the magnitude and type of precipitation, and their resulting effect on rainsplash and hydraulic erosion. The first wet season had near-normal precipitation and much of the precipitation in the lower portions of the study area fell as rain rather than snow. In the second and third wet seasons precipitation was below normal and tended to fall as snow. The resultant differences in rainfall erosivity, persistence of snow cover, and road runoff rates meant that unit area erosion rates were 3-4 times higher in the first wet season than in either of the two following wet seasons. On midslope roads with cutslopes, normalized sediment production increased as upslope soil depth decreased, and this is attributed to the increase in intercepted subsurface stormflow (ISSF).

Twenty-five percent of the surveyed road length was connected to the channel network. Stream crossings accounted for 59% of the connected road segments, and road-induced gullying accounted for another 35% of the connected road segments. The travel distance of sediment below road drainage outlets was controlled by soil erodibility, road segment length, traffic level, and the presence or absence of gullies (R^2=0.39). The likelihood of a gully below a road segment increased with longer road segment lengths on steeper slopes, with shallower soils, and road drainage designs that concentrate rather than disperse runoff. A logistic regression model using these factors had a 90% success rate in distinguishing between gullied and ungullied segments. Gully volume was significantly related to the product of road segment length and hillslope gradient, soil erodibility, and road drainage type (R^2=0.60). Gully volumes were significantly higher below relief culverts than below waterbars or rolling dips.

Both studies show that road sediment production and some aspects of sediment delivery are strongly controlled by road area (A) or road length (L), and the interaction of A or L with road gradient (S) or hillslope gradient (S_H). A*S is a surrogate for the sediment transport capacity of runoff on the road surface, and L*S_H is a surrogate for the sediment transport capacity of road runoff below a drainage outlet. Higher L*S_H values increase the likelihood that a gully will form below a drainage outlet and deliver sediment to the channel network. Frequent road drainage serves to reduce both A*S and L*S_H. An analysis of existing data on road-to-stream connectivity suggests that the absence of engineered road drainage structures increases road-stream connectivity by 40%.

Both studies indicate that the interception of subsurface stormflow (ISSF) can increase both road sediment production and sediment delivery. Variables such as soil depth and the ratio of cutslope height to soil depth have the potential to explain some of the variability in road sediment production rates and gully initiation. However, the role of ISSF is difficult to include in empirical predictive equations because of the tremendous spatial and temporal variability in the amount and interception of subsurface stormflow.

Overall, these studies show that road sediment production is best mitigated by rocking native surface roads, decreasing sediment transport capacity by improving and maintaining drainage, and avoiding unusual soil features that increase road surface and ditch runoff. Road sediment delivery can be minimized primarily through reducing the number of stream crossings, reducing the length of road segments that drain to stream crossings, rocking the approaches to stream crossings, preventing gully formation below road drainage outlets, and placing new roads further from stream channels. The results of these studies can help managers reduce road sediment production and delivery, and thereby reduce the adverse impacts of unpaved forest roads on aquatic resources.