THESIS

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

Submitted by

Allison K. Stafford

Department of Forest, Rangeland, and Watershed Stewardship

Master of Science

Spring 2011

Advisor: Lee MacDonald

Committee Members: John Stednick and Greg Butters

ABSTRACT

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

Unpaved roads often are a major source of sediment to streams in forested watersheds, and an increase in sediment production and delivery can adversely affect the overall health of a stream. The goals of this study were to first quantify the effects of climate and soil type on hillslope and road sediment production and delivery, and then evaluate the effects of graveling, grading, and waterbar construction on road sediment production and delivery. Sediment fences were used to collect 109 fence-years of data from water years 2008 and 2009 in the more rain dominated José Basin (800-1200 m) and 193 fence-years of data in the snow dominated Kings River Experimental Watersheds (KREW) (1485-2420 m), both located in Sierra National Forest (SNF) in California. Detailed road surveys assessed road segment characteristics and road-stream connectivity.

Mean hillslope sediment production in José Basin was 3.7 x 10^{-3} kg m^{-2} yr^{-1}, which was similar to the value of 4.1 x 10^{-3} kg m^{-2} yr^{-1} in KREW. Native surface road segments in José Basin had a mean sediment production rate of 1.8 kg m^{-2} yr^{-1}, and the estimated total sediment production from the 67 km of native surface roads is 680 metric tons per year. An estimated 30% of the native surface road length is connected to the stream network, indicating that up to 210 metric tons of sediment may be delivered to streams each year. There was no significant difference in sediment production and delivery between road segments in the highly erodible Holland soil and road segments in other soil types. Mean sediment production for the native surface road segments in the KREW watersheds was 0.13 kg m^{-2} yr^{-1}, which was more than an order of magnitude lower than the mean value in José Basin, and road-stream connectivity was only 3%.

There was no significant difference in sediment production from native and gravel surface road segments in José Basin due to the high variability and the gravel segments still averaged 51% bare soil. The gravel surface segments had shorter drainage features than native surface segments, but 40% of the gravel roads were connected as they tended to be closer to streams. Graveled roads in the Providence Creek watersheds produced 0.16 kg m^{-2} yr^{-1}, which was only 22% as much sediment as the native surface roads, and had 11% connectivity.

In José Basin grading initially decreased the mean segment length from 65 m to 41 m, but one year after grading 22% of the waterbars had failed, leading to a 15% increase in mean segment length. Graded road segments in José Basin produced eight and three times more sediment per unit area than ungraded segments in WY2008 and WY2009, respectively, and this can be attributed to extensive rilling. Sediment production rates decreased by 40-60% from the first to the second year after grading.

Sediment production and delivery from forest roads can be reduced by: 1) using more than 30% gravel cover on native surface roads, 2) minimizing grading, and 3) improving the construction of waterbars to better withstand and direct overland flow.

Allison K. Stafford
Department of Forest, Rangeland, and Watershed Stewardship
Colorado State University
Fort Collins, CO 80523
Spring 2011

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Lee MacDonald for his guidance, as well as Dr. John Stednick. I never could have completed this work without the astounding support of friends and family. I would especially like to thank Abby Korte for her friendship and insight throughout this process. I am very grateful to Alan Gallegos, Sierra National Forest, and Carolyn Hunsaker and the Kings River Experimental Watershed staff for their guidance, summer housing, and field support. I would also like to thank Drew Coe as well as numerous field assistants. This work has been supported by grants from the Sierra National Forest and the USDA Forest Service Region 5.

TABLE OF CONTENTS

1. INTRODUCTION

Increased sediment loading adversely impacts streams, as it can affect water quality, stream habitat, and aquatic ecosystems (Tagart, 1976; Cederholm et al., 1981; Reid and Dunne, 1984; Bilby et al., 1989; Ziegler and Giambelluca, 1997; Kolka and Smidt, 2004). Inputs of fine sediment can decrease pool depth and abundance, and increase turbidity, both of which can alter the quality and quantity of habitat for salmonids and limit reproduction (Harr and Nichols, 1993; Weaver and Hagans, 1999; Beechie et al., 2005). Increased sediment loading also affects aquatic organisms by altering the temperature and nutrient loads in the stream (Kolka and Smidt, 2004). Additionally, increased sediment delivery to reservoirs reduces the usable capacity and interferes with piping systems (Minear and Kondolf, 2009). The U.S. Environmental Protection Agency lists sediment as the most common impairment to water quality in streams and lakes in the United States (EPA, 2010).

Hillslope sediment production rates in undisturbed forested watersheds are typically very low (MacDonald et al., 2003), as forests have a dense surface cover of vegetation and litter and a high porosity and infiltration rate (Dunne and Leopold, 1978). In contrast, unpaved roads have a low infiltration rate and little to no surface cover, so they often are a major sediment source in forested watersheds (Reid and Dunne, 1984; Swift, 1988; Bilby et al., 1989; Luce and Black, 1999; Ketcheson et al. 1999; Coe, 2006). Studies spanning a variety of differently designed and surfaced roads in rain, rain-on-snow, and snow climates have found that road sediment production rates vary by two to three orders of magnitude due to differences in climate, soil type, road surface type and design, and road maintenance practices such as grading (Megahan, 1974; Reid and

Dunne, 1984; Kochenderfer and Helvey, 1987; Bilby et al., 1989; Burroughs and King, 1989; Luce and Black, 1999; Luce and Black, 2001; MacDonald et al., 2001; Ziegler et al., 2001; Appelboom et al., 2002; Clinton and Vose, 2003; Motha et al., 2004; Ramos-Scharrón and MacDonald, 2005; Barrett and Tomberlin, 2006; Coe, 2006; Forsyth et al., 2006; Sheridan and Noske, 2007; Sugden and Woods, 2007; Welsh, 2008). The large range found in these studies shows that road sediment production rates are case-specific, and rates found in one location cannot necessarily be applied elsewhere.

Road surface sediment production is the result of several erosional and transport processes. These include: 1) rainsplash detachment; 2) sheetwash; and 3) rill erosion (Zeigler et al., 2000). The absolute and relative magnitudes of these processes depend on a number of location-specific climatic and road surface variables. Road runoff and sediment production may only be a concern if this material is delivered to a stream or other water body. Road sediment delivery is determined by the amount of runoff leaving the road surface as well as the location of road drainage points relative to the stream network (Megahan and Ketcheson, 1996; Croke and Mockler, 2001; Croke et al., 2005; Croke and Hairsine, 2006; Lane et al., 2006).

Climate is one of the most important controls on road sediment production, as this affects the amount, type, and intensity of precipitation (MacDonald et al., 2001). Unpaved roads in rain dominated climates should produce much more sediment than comparable roads in snow dominated climates, as rainfall is more erosive than snow. In mountainous areas, the rain to snow ratio is largely driven by elevation. No one study has simultaneously measured and compared sediment production rates across rain, rain-on-snow, and snow dominated climates to quantify the effects of climate in one geographic area.

Soil type is another important control on road sediment production, as this affects the particle-size distribution and soil erodibility. Several studies have compared road sediment production and delivery between different soil types (Rice and Lewis, 1991; Luce and Black, 1999; Sugden and Woods, 2007), but no study has compared hillslope or road sediment production and delivery from the highly erosive Holland soil (USDA, 1983) to other soil types in California's southern Sierra Nevada.

The same factors controlling sediment production on native surface roads also control sediment production on gravel surface roads, but the relative magnitude of the various processes can differ greatly from native surface roads. Most studies have shown sediment production rates from gravel surface roads to be lower than values from comparable native surface roads, and this can be largely attributed to the protection from rainsplash and reductions in surface erodibility and overland flow velocities (Kochenderfer and Helvey, 1987; Burroughs and King, 1989; Appelboom et al., 2002; Sheridan and Noske, 2003; Barrett and Tomberlin, 2006; Coe, 2006; Forsyth et al., 2006; Korte, in preparation). However, no study has directly compared the relative effects of graveling between rain and snow dominated climates in one geographic area.

Grading is an important and common road maintenance technique when surface erosion hinders the road's drivability. Grading is often paired with the construction or re-establishment of waterbars, which drain water off the road surface and reduce the contributing area of a road segment, thereby potentially decreasing sediment production and delivery. The surface disturbance due to grading increases the supply of material for transport, thus leading to an initial increase in sediment production (Megahan and Kidd, 1972; Megahan, 1974; Reid and Dunne, 1984; Megahan et al., 1986; Luce and Black, 1999; Ziegler et al., 2000; Ziegler et al., 2001; Appelboom et al., 2002; Ramos-Scharrón and MacDonald, 2005; Coe, 2006).

Quantifying the amount and persistence of the increase in sediment production after grading is necessary for forest managers to determine the optimal frequency of grading versus maintaining the drivability of the road. Quantifying the effect of grading on waterbar frequency and performance is necessary to determine how grading affects road sediment delivery to streams. The combination of grading and waterbar installation or maintenance may result in either an increase or decrease in sediment delivery to the stream network, depending on whether delivery is reduced enough to outweigh the increase in sediment production; hence it is important that both aspects be examined.

Forest managers need to identify the key variables for road sediment production and delivery to guide road construction and maintenance. Several studies have examined these key variables and attempted to predict road sediment production and delivery rates (Ziemer et al., 1991; Harden, 1992; Luce and Cundy, 1994; Elliot et al., 1999; Doten et al., 2006; Ramos-Scharrón and MacDonald, 2007). As with the magnitude of sediment production, the controls on sediment production vary with location and climate, and this study will quantify these variables in José Basin, a 78 km^2 rain dominated watershed in the Sierra Nevada of California.

The present study is building on previous work on road sediment production and delivery rates in the Sierra Nevada. The first of these studies was in the Eldorado National Forest in the northern Sierra Nevada (Coe, 2006). Sediment production rates were measured for three water years (WY2000 to WY2002) for 15 native surface road segments that were not recently graded, for 2-40 road segments graded within the past two years, and for 9-10 gravel surface road segments. Elevations were between 1000 and 1800 m, so the area has a highly variable mixture of rain and snow. Segment-scale measurements and road surveys were used to determine the dominant controlling variables and predict road sediment production and delivery (Coe, 2006).

The second study was in the higher elevation (1485-2420 m), rain-on-snow and snow dominated Kings River Experimental Watershed (KREW) in the Sierra National Forest (SNF) (Korte, in preparation). This study quantified sediment production rates from WY2004 through WY2006 for: 9-20 hillslopes; 23-34 native, gravel, and mixed surface road segments; and seven ditches adjacent to paved roads. This study also determined key variables for predicting sediment production and used road surveys to evaluate sediment delivery pathways and (Korte, in preparation). These data were combined with three additional years of monitoring under the present study to allow more direct comparisons between KREW and José Basin.

The overall goals of this study were to: 1) compare sediment production rates from hillslopes and forest roads in rain and snow dominated climates; 2) evaluate the effects of graveling and grading on road sediment production and delivery; and 3) predict road sediment production rates in José Basin. Chapter 2 of this thesis quantifies the effects of elevation and soil type on sediment production and delivery by: 1) comparing sediment production rates from undisturbed hillslopes and native surface road segments between the snow dominated KREW watersheds and the rain dominated José Basin; 2) comparing sediment production rates from hillslopes and native surface road segments on

Holland soil and other, less erosive soils in José Basin; and 3) estimating sediment production and delivery from native surface roads in José Basin.

Chapter 3 quantifies the effects of graveling, grading, and waterbar construction and maintenance on sediment production and delivery by: 1) comparing sediment production and delivery between native and gravel surface roads; 2) estimating total sediment production and delivery from gravel surface roads in José Basin; and 3) quantifying the effect of grading and waterbar installation on road segment characteristics, road sediment production, and road sediment delivery in José Basin.

Forest managers must constantly work to balance public accessibility and forest conservation. While roads are necessary for public accessibility and management activities, they may negatively affect water quality and stream health. The results of this study help quantify the variations in road sediment production and delivery from hillslopes and roads in different climates in the SNF, and guide management practices to reduce road sediment contributions while maintaining drivability.

1.1. Literature cited

Appelboom, T.W., G.M. Chescheir, R.W. Skaggs, and D.L. Hesterberg. 2002. Management practices for sediment reduction from forest roads in the coastal plains. *American Society of Agricultural Engineers* **45(2)**: 337-344.

Barrett, B., and D. Tomberlin. 2008. Sediment production on forest road surfaces in California's redwood region: results for HY2006 and HY2007. California Board of Forestry and Fire Protection-Monitoring Study Group Meeting, February 13, 2008, Redding, CA, USA.

Beechie, T.J., C.N. Veldhuisen, E.M. Beamer, D.E. Schuett-Hames, R.H. Conrad, and P. DeVries. 2005. Monitoring treatments to reduce sediment and hydrologic effects from roads. In: *Monitoring Stream and Watershed Restoration*, Roni, R. (ed.). America Fisheries Society, Bethesda, MD, USA. Pp. 35-65.

Bilby, R.E., K. Sullivan, and S.H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds of south-western Washington. *Forest Science* **35**: 453-468.

Burroughs, E.R., and J.G. King. 1989. Reduction of soil erosion on forest roads. USDA Forest Service GTR-INT-261, Ogden, UT, USA. 21 pp.

Cederholm, C.J., L.M. Reid, and E.O. Salo. 1981. Cumulative effects of logging road sediment on salmonids populations in the Clearwater River, Jefferson County, Washington. In: *Salmon-Spawning Gravel: A Renewable Resource in the Pacific Northwest?* Washington Water Research Center, Pullman, WA, USA. Pp. 38-74.

Clinton, B.D., and J.M. Vose. 2003. Differences in surface water quality draining four road surface types in the southern Appalachians. *Southern Journal of Applied Forestry* **27(2)**: 100-106.

Coe, D. 2006. Sediment production and delivery from forest roads in the Sierra Nevada, California. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 107 pp.

Croke, J.C., and P.B. Hairsine. 2006. Sediment delivery in managed forests: A review. *Environmental Review* **14**: 59-87.

Croke, J., and S. Mockler. 2001. Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms* **26**: 205-217.

Croke, J., S. Mockler, P. Fogarty, and I. Takken. 2005. Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. *Geomorphology* **68**: 257-268.

Doten, C.O., L.C. Bowling, J.S. Lanini, E.P. Maurer, and D.P. Lettenmaier. 2006. A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds. *Water Resources Research* **42**: 1-15.

Dunne, T., and L. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman and Co., New York, NY, USA.

Elliot, W.J., R.B. Foltz, and C.H. Luce. 1999. Modeling low-volume road erosion. *Transportation Research Record* **1652**: 244-249.

EPA, 2010. What is sediment pollution? United States Environmental Protection Agency. <www.epa.gov/owow_keep/NPS/toolbox/other/KSMO_Sediment.pdf>.

Forsyth, A.R., K.A. Bubb, and M.E. Cox. 2006. Runoff, sediment loss and water quality from forest roads in a southeast Queensland coastal plain *Pinus* plantation. *Forest Ecology and Management* **221**: 194-206.

Harden, C.P. 1992. Incorporating roads and footpaths in watershed-scale hydrologic and soil erosion models. *Physical Hydrology* **13(4)**: 368-385.

Harr, R.D., and R.A. Nichols. 1993. Stabilizing forest roads to help restore fish habitats: A northwest Washington example. *Fisheries* **18(4)**:18-22.

Ketcheson, G.L., W.F. Megahan, and J.G. King. 1999. “R1-R4” and “BOISED” sediment prediction model tests using forest roads in granitics. *Journal of American Water Resources Association* **35(1)**: 83-98.

Kochenderfer, J.N., and J.D. Helvey. 1987. Using gravel to reduce soil losses from minimum-standard forest roads. *Journal of Soil and Water Conservation* **42(1)**: 46-50.

Kolka, R.K., and M.F. Smidt. 2004. Effects of forest road amelioration techniques on soil bulk density, surface runoff, sediment transport, soil moisture, and seedling growth. *Forest Ecology and Management* **202**: 313-323.

Korte, A. In preparation. Effects of surface type on sediment production and delivery from forest roads in the Sierra Nevada, California. M.S. thesis, Colorado State University, Fort Collins, CO, USA.

Lane, P.N.J., P.B. Hairsine, J.C. Croke, and I. Takken. 2006. Quantifying diffuse pathways for overland flow between the roads and streams of the Mountain Ash forests of central Victoria Australia. *Hydrological Processes* **20**: 1875-1884.

Luce, C.H., and T.A. Black. 1999. Sediment production from forest roads in western Oregon. *Water Resources Research* **35(8)**: 2561-2570.

Luce, C.H., and T.A. Black. 2001. Effects of traffic and ditch maintenance on forest road sediment production. In: *Proceedings of the Seventh Federal Interagency Sedimentation Conference*. March 25-29, 2001. Reno, NV, USA. Pp. V67-V74.

Luce, C.H. and T.W. Cundy. 1994. Parameter identification for a runoff model for forest roads. *Water Resources Research* **30(4)**: 1057-1069.

MacDonald, L.H., D. Coe, and S. Litschert. 2003. Assessing cumulative watershed effects in the central Sierra Nevada: Hillslope measurements and catchment-scale modeling. In: *Proceedings of the Sierra Nevada Science Symposium: Science for Management and Conservation* PSW-GT-193. Pp. 149-157.

MacDonald, L.H., R.W. Sampson, and D.M. Anderson. 2001. Runoff and road erosion at the plot and road segment scale, St. John, U.S. Virgin Islands. *Earth Surface Processes and Landforms* **26**: 1-22.

Megahan, W.F. 1974. Erosion over time: A model. USDA Forest Service Research Paper INT-156, Ogden, UT, USA. 14 pp.

Megahan, W.F., and G.L. Ketcheson. 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. *Water Resources Bulletin* **32(2)**: 371-382.

Megahan, W.F., and W.J. Kidd. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. *Journal of Forestry* **70(3)**:136-141.

Megahan, W.F., Seyedbagheri, K.A., and T.L. Mosko. 1986. Construction phase sediment budget for forest roads in granitic slopes in Idaho. In *Drainage Basin Sediment Delivery*, Hadley, R.F. (ed.). IAHS Publication 159: 31-39.

Minear, J.T. and G.M. Kondolf. 2009. Estimating reservoir sedimentation rates at large spatial- and temporal-scales: a case study of California. *Water Resources Research* **45(12)**: W12502-W12509.

Motha, J.A., P.J. Wallbrink, P.B. Hairsine, and R.B. Grayson. 2004. Unsealed roads as suspended sediment sources in an agricultural catchment in south-eastern Australia. *Journal of Hydrology* **286**: 1-18.

Ramos-Scharrón, C.E., and L.H. MacDonald. 2005. Measurement and prediction of sediment production from unpaved roads, St John, US Virgin Islands. *Earth Surface Processes and Landforms* **30**: 1283-1304.

Ramos-Scharrón, C.E., and L.H. MacDonald. 2007. Development and application of a GIS-based sediment budget model. *Journal of Environmental Management* **84**: 157-172.

Reid, L.M., and T. Dunne. 1984. Sediment production from forest road surfaces. *Water Resources Research* **20(11)**: 1753-1761.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agricultural Handbook No 703. 324 pp.

Rice, R.M., and J. Lewis. 1991. Estimating erosion risks associated with logging and forest roads in northwestern California. *Water Resources Bulletin* **27(5)**: 809-818.

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

Swift Jr., L.W. 1988. Forest access roads: Design, maintenance, and soil loss. In: *Forest Hydrology and Ecology at Coweeta.* Swank, W.T., and D.A. Crosley, Jr. (eds.). Springer-Verlag, New York, USA. Pp. 313-324.

Sugden, B.D., and S.W. Woods. 2007. Sediment production from forest roads in Western Montana. *Journal of the American Water Resources Association* **43(1)**: 193-206.

Tagart, J.V. 1976. The survival from egg deposition to emergence of Coho salmon in the Clearwater River, Jefferson County, Washington. M.S. thesis, University of Washington, Seattle, WA, USA. 101 pp.

USDA Forest Service. 1983. Soil survey of Sierra National Forest area, California. USDA Forest Service, Pacific Southwest Region: Auberry, Cascadel Point, Musick Mtn., and Shaver Lake Quadrangles. 1:24,000.

Weaver, W., and D. Hagans. 1999. Storm-proofing forest roads. In: *Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium*, OSU Department of Forest Engineering and International Union of Forestry Research Organizations, Corvallis, OR, USA. Pp. 230-245.

Welsh, M.J. 2008. Sediment production and delivery from forest roads and off-highway vehicle trails in the upper South Platte River watershed, Colorado. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 154 pp.

Ziegler, A.D., and T.W. Giambelluca. 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. *Journal of Hydrology* **196**: 204-229.

Ziegler, A.D., R.A. Sutherland, and T.W. Giambelluca. 2000. Partitioning total erosion on unpaved roads into splash and hydraulic components: The roles of interstorm surface preparation and dynamic erodibility. *Water Resources Research* **36(9)**: 2787-2791.

Ziegler, A.D., R.A. Sutherland, and T.W. Giambelluca. 2001. Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads. *Earth Surface Processes and Landforms* **26**: 235-250.

Ziemer, R.R., J. Lewis, R.M. Rice, and T.E. Lisle. 1991. Modeling the cumulative watershed effects of forest management strategies. *Journal of Environmental Quality* **20(1)**: 36-42.

2. EFFECTS OF CLIMATE AND SOIL TYPE ON HILLSLOPE AND NATIVE SURFACE ROAD SEDIMENT PRODUCTION AND DELIVERY

ABSTRACT:

Sediment is the dominant non-point source pollutant in streams, and unpaved roads are often considered to be a major source of sediment in forested watersheds. The overall goal of this study was to assess sediment production and delivery from hillslopes and roads in two study areas in the southern Sierra Nevada of California. The first study area, José Basin, is a 78 km^2 rain dominated watershed, and the second was the Kings River Experimental Watershed (KREW), which contains two groups of four small, snow dominated watersheds. Sediment production was measured with sediment fences for two water years in José Basin, and up to six water years in KREW. The specific objectives were to: 1) quantify the effects of climate on sediment production and delivery rates from hillslopes and native surface road segments; 2) quantify the effects of soil type on sediment production and delivery rates from hillslopes and native surface road segments in José Basin; and 3) estimate the total sediment production and delivery from native surface roads in José Basin.

In José Basin, the mean hillslope sediment production rate was 3.7 x 10^{-3} kg m^{-2} yr^{-1}, and for native surface roads the value was 1.8 kg m^{-2} yr^{-1}, or nearly 500 times higher. Hillslope and road sediment production rates were not significantly different between the highly erodible Holland soils and other soil types. Rilled road segments produced significantly more sediment than segments without rills. Detailed road surveys and an empirical model indicate that native surface roads in José Basin produce 680 metric tons yr^{-1} of sediment and potentially deliver 210 metric tons yr^{-1} to the stream network. Much of this sediment is coming from a relatively few segments with extensive rilling that are located close to a stream.

At the higher elevation KREW sites the mean sediment production rates for hillslopes and roads were an order of magnitude lower than in José Basin. The potential increase in air temperatures due to climate change and the associated shift from snow to rain will increase hillslope road erosion rates as well as sediment delivery to streams. Management practices to reduce road sediment production and delivery should focus in rain dominated climates where erosion rates are likely to be higher than in snow dominated areas.

Allison K. Stafford
Department of Forest, Rangeland, and Watershed Stewardship
Colorado State University
Fort Collins, CO 80523
Spring 2011

2.1. Introduction

Increased sediment loading to streams, rivers, and lakes is a major concern, as this can adversely affect water quality, stream habitat, and aquatic ecosystems (Bilby et al., 1989; Ziegler and Giambelluca, 1997; Kolka and Smidt, 2004). Fine sediment also can decrease pool depth and abundance, and increase the turbidity of the stream (Beechie et al., 2005), both of which can alter the quality and quantity of habitat for salmonids and limit reproduction (Harr and Nichols, 1993; Weaver and Hagans, 1999; Beechie et al., 2005). Increased sediment loading affects aquatic organisms by altering the temperature and nutrient loads in the stream (Kolka and Smidt, 2004). Sediment is the most common impairment to water quality in streams and lakes in the United States (EPA, 2010). Additionally, increased sediment delivery reduces reservoir capacity and can clog or damage pipes (Minear and Kondolf, 2009).

Hillslope sediment production rates in undisturbed forested watersheds are typically very low (MacDonald et al., 2004), as forests have a dense surface cover of vegetation and litter and a high porosity and infiltration rate (Dunne and Leopold, 1978). These characteristics largely prevent soil detachment and overland flow (Dunne and Leopold, 1978). Surface disturbances such as fire, concentrated grazing, and road construction can expose the mineral soil and greatly reduce the infiltration rate (MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2005). This increases rainsplash erosion and the likelihood of erosive overland flow, which can detach soil particles and transport them to the stream network.

The surface of an unpaved road is typically dominated by exposed mineral soil, and in forested watersheds unpaved roads are often a major source of sediment to streams

(Reid and Dunne, 1984; Swift, 1988; Bilby et al., 1989; Luce and Black, 1999; Ketcheson et al. 1999; Coe, 2006). Unpaved roads can deliver a large amount of sediment to streams relative to their surface area even during low to moderate rainfall events due to their characteristically low infiltration rates (Ziegler and Giambelluca, 1997; Chappell et al., 1999; Ziegler et al., 2004; Cafferata et al., 2007).

The amount of road sediment delivered to streams is determined by the amount of runoff leaving the road surface as well as the location of drainage points relative to streams. While several studies have examined road sediment delivery pathways (Megahan and Ketcheson, 1996; Croke and Mockler, 2001; Croke et al., 2005; Croke and Hairsine, 2006; Lane et al., 2006), both road sediment production and sediment delivery are highly location-specific, as they depend on variables such as climate, soil type, slope, and surface cover. Numerous attempts have been made to predict sediment production and delivery for a range of climates and types of roads, most notably by using the physically-based WEPP:Road model. However, more accurate estimates may be obtained by measuring road segment characteristics and sediment production rates for a specific area or climate, and developing local empirical models. Alternatively, such data also can be used to test the validity of WEPP:Road or other models.

Sediment production and delivery from forest roads has been monitored in the Sierra Nevada mountains in California by Colorado State University graduate students since 1999. The first study in the Eldorado National Forest in the northern Sierra Nevada (Figure 2.1) measured sediment production rates from 15 native surface road segments that were not recently graded from water year (WY) 2000 to WY2002 (Coe, 2006). Elevations ranged from 1000 to 1800 m, and the area has a mixed rain and snow climate.

Mean annual sediment production from the native surface road segments varied from 0.22 to 0.81 kg m^{-2}, and road surveys indicated that 25% of the road length was hydrologically connected to the stream network (Coe, 2006). .

The second study was located further south in the Sierra National Forest (SNF) in the Kings River Experimental Watershed (KREW) (Figure 2.1). This study monitored sediment production from 9-18 undisturbed hillslopes and 11-22 native surface road segments from WY2004 to WY2006 (Korte, in preparation). Elevations ranged from 1485 to 2420 m, and the area is snow and rain-on-snow dominated. The mean sediment production rate on undisturbed hillslopes was 0.01 kg m^{-2} yr^{-1} (s.d. = 0.02 kg m^{-2} yr^{-1}), and mean annual production rates for hillslopes in the mid-elevation Providence Creek watersheds (1485-2005 m) were similar to the mean values for the upper elevation Bull Creek watersheds (2050-2420 m). The mean values for native surface road segments ranged from 0.0 to 6.2 kg m^{-2} yr^{-1}, and the overall mean road erosion rate of 0.74 kg m^{-2} yr^{-1} (s.d. = 1.2 kg m^{-2} yr^{-1}) was comparable to the higher values from the Eldorado National Forest. In contrast to the hillslopes, the mean annual sediment production rate for the native surface road segments in the Providence Creek watersheds was 4-15 times the value for the Bull Creek watersheds. The high interannual variability and high variability among segments within a water year indicated a need for continued monitoring and data analysis.

The present study continued monitoring sediment production rates from undisturbed hillslopes and road segments in the KREW watersheds, but the primary focus was shifted to José Basin, a 78 km^2 watershed located 20 km west of KREW. Road sediment production rates in José Basin are expected to be higher than values found by the two previous studies as the climate is rain rather than snow dominated. Hence the goals of this study were to measure sediment production and delivery from hillslopes and forest roads in José Basin from different soil types, and use these data to examine the effects of climate on sediment production and delivery.

2.2. Background

Water-driven erosion at the road segment scale depends on several interacting erosion and transport processes, including rainsplash, sheetwash, and rill erosion (Zeigler et al., 2000). Rainsplash detachment occurs when the impact from a falling raindrop detaches sediment particles (Zeigler et al., 2000). The rate of rainsplash detachment is highly dependent on the rainfall erosivity, which in turn is a function of the precipitation intensity and the drop size distribution (Lal, 1988; Renard et al., 1997). Snowfall has minimal erosive energy, as it is lighter and falls much more slowly than rain. Rainsplash is minimal on forested, undisturbed hillslopes, as the surface is protected by vegetation and litter (Dunne and Leopold, 1978), but it can play a major role in sediment production from native surface roads (Ziegler et al., 2000). In Thailand, which has a monsoonal rainfall climate, rainsplash detachment accounted for 38-45% of sediment production from the road surface, even though the surface was highly compacted (Ziegler et al., 2000).

When rainfall intensity exceeds the infiltration capacity of a surface, water flows downslope as infiltration-excess or Horton overland flow (HOF), which can result in sheetwash and/or rill erosion (Dunne and Leopold, 1978). Sheetwash occurs when water flows across the surface in a sheet, detaching and transporting sediment (Dunne and

Leopold, 1978). Rill erosion is when water collects into channels due to the surface's micro-topography. The concentrated flow can detach and transport sediment from the rill bed and sides (Dunne and Leopold, 1978).

Both sheetwash and rill erosion occur when the shear stress applied by the flow exceeds the resistance of the surface (Dunne and Leopold, 1978; Luce and Black, 1999; Croke and Hairsine, 2006). The shear stress of a given flow is given by

$$\tau = \gamma dS \qquad \text{(equation 2.1)}$$

where τ is the shear stress (Newtons m^{-1}), γ is the fluid density (Newtons m^{-2}), d is the depth of flow (m), and S is the surface slope (m m^{-1}). The depth of flow is a function of the duration and intensity of a given precipitation event relative to the infiltration rate. In the Sierra Nevada, snowmelt rates are typically much lower than rainfall intensities, allowing more time for the snowmelt to infiltrate and resulting in a much lower likelihood of HOF.

Infiltration rates on undisturbed, forested hillslopes are high, and HOF rarely occurs (Dunne and Leopold, 1978). Infiltration rates for unpaved roads tend to be very low; values in Idaho, Colorado, and Montana varied between 5×10^{-5} and 8.8 mm h^{-1} with a geometric mean of 0.11 mm h^{-1} (Luce and Cundy, 1994). Therefore, assuming a spatially uniform precipitation rate, the discharge from a road segment is directly proportional to the area of that segment, while the velocity of the flow is directly proportional to the slope of a road segment (Ramos-Scharrón and MacDonald, 2007). The rainsplash detachment, shear stress of HOF, and resulting transport capacity are direct functions of the precipitation characteristics and the contributing area and slope of a road segment (Anderson and MacDonald, 1998; MacDonald et al., 2004).

As runoff becomes channelized into rills, the detachment and transport capacity increases because the flow is deeper and faster (Merz and Bryan, 1993; Brunton and Bryan, 2000). The extent of rilling will vary with soil properties and precipitation characteristics (Brunton and Bryan, 2000). In Colorado, road sediment production was strongly related to rill density ($R^2 = 0.57$, $p < 0.0001$) (Welsh, 2008). In agricultural and burned areas, rill erosion may be more important than sheetwash erosion (Pietraszek, 2006), but few data are available on the balance between sheetwash and rill erosion for unpaved roads.

Soil type is another important control on road sediment production, as this affects the soil erodibility. Soil erodibility is one of the controlling factors in the Revised Universal Soil Loss Equation (RUSLE), and this is calculated from the soil texture, organic matter content, structure, and permeability (Renard et al., 1997). In José Basin, the soils in the Holland series are notably more erosive as the soil erodibility (K factor) in RUSLE is 0.28. This is higher than the values of 0.20 or less for all other soil types (USDA, 1983). Exposure of the sandy clay loam B horizon is thought to especially lead to surface erosion. This has led to more extensive rocking and other treatments on roads in Holland soils (A. Gallegos, pers. comm., USDA Forest Service, 2007).

Road-stream connectivity determines the hydrologic effects of roads at the watershed scale (Wemple et al., 1996; La Marche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001). Sediment from roads is contributed to the stream network when sediment produced exits the road surface and flows into a stream (Croke and Mockler, 2001), such as at stream crossings (Wemple et al., 1996; Croke and Mockler, 2001; Coe, 2006). Road-stream crossings are rare in the two study areas, so most of the road-stream connectivity is due to the concentrated runoff from a road extending to a stream as evidenced by a sediment plume or small channel (Montgomery, 1994; Wemple et al., 1996; Croke and Mockler, 2001; La Marche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001).

Road sediment production and delivery modeling is necessary to estimate the amount of sediment delivered from roads to streams, and modeling also can help direct management practices to those road segments with the highest potential for sediment delivery. The most common road sediment production and delivery model is WEPP:Road, a web-based interface based on the Water Erosion Prediction Project (WEPP). This is designed to predict sediment production and delivery from road segments, compacted landings, compacted skid trails, and compacted foot, cattle, or off-road vehicle trails (Elliot, 1999). WEPP:Road is a process-based model which only requires users to specify key variables, namely the climate, soil type, gravel cover, local topography, segment length, segment slope, road design, surface conditions, ditch conditions, and distance to streams.

2.3. Objectives

Given this background, the specific objectives were to: 1) measure sediment production rates from undisturbed hillslopes and native surface road segments in KREW and José Basin; 2) use these data to quantify the effects of climate on sediment production and delivery; 3) quantify the effects of soil type on hillslope and road sediment production and delivery in José Basin; 4) estimate the basin-wide annual native surface road sediment production and delivery rate for José Basin; and 5) compare the measured road sediment production rates to modeled values using WEPP:Road. Working hypotheses were that road sediment production rates would be higher in rain dominated climates than in snow dominated climates, and higher on roads in Holland soils than other soil types. Sediment production rates from undisturbed hillslopes also were expected to be significantly less than values from native surface roads.

2.4. Methods

2.4.1. Site description

José Basin

José Basin is a 78 km^2 watershed in Sierra National Forest, located in the southern Sierra Nevada of California (Figure 2.1). Elevations range from 450 to 1950 m (Figure 2.2), although most of the study sites were located between 800 and 1200 m. The area has a Mediterranean-type climate with dry summers and wet winters. Most precipitation at the lower elevations falls as rain, and in the upper portions of the basin there is usually a seasonal snowpack and rain-on-snow events occur frequently due to diurnal and seasonal fluctuations (A. Gallegos, USFS, pers. comm., 2008).

The middle and upper elevations in José Basin are dominated by conifers, particularly ponderosa pine (*Pinus ponderosa*) and incense cedar (*Libocedrus decurrens*). At lower elevations, brush stands are more common, and these contain ceanothus (*Ceanothus* spp.), manzanita (*Arctostaphylos* spp.), and other species. Primary soil types are the Shaver, Tollhouse, Chawanakee, and Holland series (USDA, 1983). As stated earlier, Holland soils are regarded as being particularly susceptible to surface erosion (A. Gallegos, USFS, pers. comm., 2007).

There are 447 km of stream channels in José Basin and the drainage density is 5.7 km km^{-2} (Figure 2.3) (SNF data base, accessed via A. Gallegos, 2007). The basin has an extensive road network, with 159 km of mapped roads for a relatively high road density of 2.0 km km^{-2} (Figure 2.3) (SNF data base, accessed via A. Gallegos, 2007). The mean road width is approximately 2.6 m, indicating that roads occupy only 0.53% of the total surface area. Much of the basin is managed by the SNF, but there are extensive private land holdings. Road access is crucial in José Basin as there are scattered houses in some areas, and the basin is heavily used for grazing, logging, and recreational uses such as hunting and off-highway vehicles.

Providence and Bull Creek Watersheds, KREW

The Kings River Experimental Watershed (KREW) is 20 km east of José Basin, and is also in the SNF (Figure 2.1). KREW contains two groups of four watersheds; the lower elevation group is the Providence Creek watersheds (1485 to 2005 m) (Figure 2.4a), and the higher elevation group is the Bull Creek watersheds (2050 to 2420 m) (Figure 2.4b). The eight watersheds range in size from 0.53 to 2.27 km^2. Average annual precipitation is 1240 mm, with approximately 90% of the precipitation falling as snow, and the Bull Creek watersheds typically have a higher snow to rain ratio than the Providence Creek watersheds (Korte and MacDonald, 2007). Vegetation in the Providence Creek watersheds is primarily Sierra mixed-conifer forest, while the Bull Creek watersheds have Sierra mixed-conifer forest that grades into red fir (*Abies magnifica)* at higher elevations. The KREW watersheds have primarily Gerle, Cagwin, and Shaver series soils, which are coarse sandy loam and loamy sand soils with granitic lithology (USDA, 1983).

2.4.2. Precipitation

José Basin

Five tipping bucket rain gages were installed in José Basin (Figure 2.2), but equipment problems and vandalism meant that valid data were collected from four rain gages in WY2008 and three gages in WY2009. Annual precipitation and annual erosivity were calculated using the RF program for each gage for WY2008 and WY2009 (Petkovsek, 2001). No correlation was found between elevation and annual precipitation or annual erosivity for either water year, so data from the nearest functioning rain gage were assigned to each site where sediment production was measured.

The precipitation data from José Basin was put in historical context by using the 95 years of precipitation data from the Auberry climate station, which is the closest long-term station. The elevation of the Auberry station is 640 m and it is approximately 10 km west of José Basin (Figure 2.1). Annual precipitation from the rain gages in José Basin was compared to the long-term mean annual precipitation and the measured precipitation at Auberry for WY2008 and WY2009.

Providence Creek and Bull Creek watersheds, KREW

Precipitation data were collected at 15-minute intervals at upper and lower climate stations in both the Providence Creek and Bull Creek watersheds for WY2008 and WY2009 (Table 2.1). The precipitation gages in the Providence Creek watersheds are at 1750 m and 1985 m, while the gages in the Bull Creek watersheds are at 2195 m and 2463 m. Annual erosivity was calculated. Regression equations between elevation and either annual precipitation or annual erosivity were calculated separately for the Providence Creek and Bull Creek watersheds, and these equations were used to calculate the annual precipitation and erosivity for each of the hillslopes and road segments where sediment production was being monitored. In WY2009 the data for the lower Bull Creek precipitation gage were incomplete, so data from the upper gage were used for all of the sites in the Bull Creek watersheds.

2.4.3. Hillslope sediment production and characteristics

Hillslope sediment production and characteristics were measured for 9-18 undisturbed convergent hillslopes in KREW and 10 hillslopes in José Basin. Sediment production was measured by installing a sediment fence in each convergent swale (Figure 2.5). These were constructed of a geotextile fabric attached to 1.2 m long pieces of 1.3 cm diameter rebar that were pounded 0.3-0.5 m into the ground (Robichaud and Brown, 2002). The leading edge of the fabric was attached to the ground with landscape staples to prevent underflow.

Annual sediment production was determined by removing and weighing the sediment captured in each fence to the nearest 0.5 kg. Two representative samples of this material were analyzed for percent moisture (Gardner, 1986) and percent organic matter (Ben-dor and Banin, 1989). The mean moisture and organic matter values from each fence were used to convert the field weights to a dry mass of mineral sediment. Annual sediment production was the dry mass of mineral sediment divided by the contributing area.

Hillslope characteristics were measured and related to sediment production (Table 2.2). The drainage area for each hillslope was determined by walking and flagging the perimeter and then recording these points with a GPS and downloading these data into ArcMap. The axis and sideslope gradients were measured with a clinometer and the axis length was measured with a cloth tape. The dominant soil type was determined by digging a hole up to approximately one meter deep to observe whether there was the distinctive red-colored B horizon of a Holland soil. Soil type was grouped into either Holland or other. Other soil types included the Shaver, Tollhouse, and Chawanakee series (USDA, 1983).

The thickness of the O horizon was measured at three evenly-spaced locations along each of three evenly-spaced lateral transects. Percent cover was determined by classifying the surface at a minimum of 100 systematically-spaced points along the three transects using the categories listed in Table 2.2.

Sediment production was measured for ten hillslopes in José Basin in WY2008 and WY2009 (Table 2.3). Three hillslopes were in Holland soil and seven hillslopes were in other soil types. Sediment production also was measured from 9-10 hillslopes in the Providence Creek watersheds and 6-8 hillslopes in the Bull Creek watersheds in WY2008 and WY2009 (Table 2.4).

2.4.4. Road sediment production

Sediment production from native surface road segments with a well-defined drainage area and a single outlet was measured using sediment fences (Robichaud and Brown, 2002) (Figure 2.6). When necessary, additional fences were constructed directly downslope of the original fence to increase storage capacity and catch efficiency. The sediment production rates were calculated in the same manner as described for the hillslopes, assuming that all the sediment was derived from the road.

Sediment fences in the Providence and Bull Creek watersheds were installed by Colorado State University students prior to the current study, and annual sediment production rates for road segments in the Providence Creek watersheds were measured for WY2008 and WY2009 (Table 2.4). In José Basin road sediment production was measured from 5-12 segments in other soil types and 8-18 segments in Holland soil in WY2008 and WY2009 (Table 2.3). More than half of the sediment fences in José Basin overtopped in WY2008, and sediment production from overtopped fences were not included in the sample sizes or the mean sediment production rates.

2.4.5. Road segment characteristics

Key characteristics were measured or classified for each road segment with a sediment fence (Table 2.5). The length of each segment was measured with a meter wheel. The active width is the width of the road that is regularly driven on, while the total width is the width from the bottom of the cutslope to the top of the fillslope. Road segment area was the segment length times the active width. Segment slope was measured with a clinometer for each change of slope within the segment, and the segment slope was the length-weighted slope.

The percent surface cover was determined by classifying the surface at a minimum of 100 systematically spaced points sampled along a zigzag transect on the active road surface. Each point was classified as bare soil, gravel (defined as rock with a secondary axis greater than 1.0 cm), litter, or live vegetation. Native surface segments were defined by having less than 20% gravel cover.

Traffic levels were estimated by determining the branch order of the road relative to a main road. The traffic level of each segment was classified as very low, indicating that vehicles very rarely travelled on the road, low, medium, or high. Drain types and drain features were classified following the categories in Table 2.6. The elevation and location of the drainage point of each segment was determined using a GPS unit. The soil type of the segment was determined for each segment in José Basin by using soil maps and verifying the classification in the field. Soil types were grouped into either Holland or other, which included the Shaver, Tollhouse, and Chawanakee series (USDA, 1983). Road segment characteristics in the Providence and Bull Creek watersheds were measured by A. Korte (in preparation) prior to this study, though road surface cover was re-measured in summer 2009.

2.4.6. Road surveys

Detailed road surveys were conducted on 10.9 km of roads in José Basin between 2007 and 2009 to: 1) determine how well the fenced segments represented the road network in José Basin; and 2) estimate total annual sediment production and delivery from native surface roads in José Basin. The detailed surveys measured or estimated the same characteristics as were observed on road segments with sediment fences (Table 2.5), with the exception that the percent bare soil and gravel on the surface of the road were estimated in the surveys rather than determined with cover counts. The sections to be surveyed in José Basin were identified by breaking the road network into 269 sections that were 300 to 900 m long using ArcGIS, and selecting 20% of the road sections using a random number generator (Figure 2.7). The selected sections were surveyed unless they were paved or not accessible as they were on private land holdings. Surveys were conducted on all of the road segments in the Providence Creek and Bull Creek watersheds by A. Korte (in preparation) prior to the current study.

2.4.7. Road sediment delivery

The potential for runoff and sediment to be delivered to the stream network for each monitored and surveyed road segment was evaluated by identifying and following any sediment plume or drainage rill, hereafter referred to as drainage features (Coe, 2006). The length and slope of each drainage feature was measured (Table 2.5). The roughness of the drainage pathway was classified from one to four, with class one being very smooth pathways and class four paths having some combination of live vegetation, large woody debris, or larger litter accumulations, such as pine cones, to disrupt the flow and effectively trap the runoff and sediment.

The presence or absence of pushouts at the drainage point of the road segment was recorded (Table 2.5). Pushouts were classified as no longer intact either if they were filled with too much deposition for the water to continue to drain at that point, or the road drainage was no longer directed to the pushout. The presence or absence of large, round rocks used as armoring at the drainage point or a small channel over the road was also recorded. This drain armoring was classified as intact if it remained in the correct location to slow flow and trap sediment, and it also was noted whether the armoring was buried under sediment. The locations of culverts were noted, and the percent of the culvert that was plugged with sediment or large woody debris was estimated. The presence and volume of scour at the downstream end of each culvert was measured.

Each road segment was also put in a connectivity class according to the drainage feature length and whether it extended to within 10 m of a stream (Table 2.7). Segments with a connectivity class of one have very little potential to deliver runoff and sediment to a stream channel, while segments with a connectivity class of four have a high delivery potential.

2.4.8. Comparison to WEPP:Road

The measured sediment production values for the native surface road segments in José Basin in WY2009 were compared to the values predicted by WEPP:Road (n = 43). The northing, westing, and elevation for each fence as demarcated by a GPS unit were entered into the PRISM model for calculating the mean monthly rainfall for each native surface segment with a sediment fence. Segments on Holland soil were classified as clay loam, while segments on other soil types were classified as loam. The road surface for each segment was classified as native. Percent rock was calculated from the cover counts conducted on each monitored segment, and the road gradient, length, and width were all measured in the field. Insloped segments and segments that were a mixture of insloped and planar were classified as “insloped with a bare ditch”. Outsloped segments with berms and planar segments were classified as “outslope, rutted” since these segments generally had at least some wheel ruts. . Low and medium traffic levels were set as low, while very low traffic levels were set as none. The length of the simulated climate was set to one year. WEPP:Road was validated by comparing predicted rates to measured values.

2.4.9. Statistical analysis

The main dependent variable was the annual sediment production rate from hillslopes and native surface road segments (kg m^{-2} yr^{-1}). Pairwise comparisons of hillslope and road segment sediment production rates for WY2008 and WY2009 were made between each of the study areas: José Basin, the Providence Creek watersheds, and the Bull Creek watersheds. The effect of soil type on hillslope and road sediment production in José Basin also was evaluated by pairwise comparisons between Holland and other soil types for WY2008 and WY2009. The validity of each comparison was assessed by comparing other key variables (e.g., slope, area, percent bare soil) between groups.

ANOVA tables and regressions were used to assess the relationships between each independent variable and the measured sediment production rates from native surface road segments in José Basin from WY2008 and WY2009. A multivariate linear regression model to predict sediment production from native surface road segments in José Basin was constructed using a backward elimination procedure and a selection criteria of $\alpha = 0.10$. The multivariate model was evaluated by comparing predicted sediment production rates to measured values.

2.5. Results

2.5.1. Precipitation

José Basin

Mean annual precipitation for the past 95 years at the Auberry rain gage is 611 mm (California Department of Water Resources, 2010). In WY2008 the annual precipitation at Auberry was only 458 mm or 75% of the mean. Mean precipitation for the four functioning rain gages in José Basin in WY2008 was 519 mm (standard deviation (s.d.) = 50 mm), or approximately 60 mm more than at Auberry (Figure 2.8). Annual precipitation was not significantly correlated with elevation in José Basin for WY2008 ($R^2 = 0.03$, $p = 0.84$). The mean erosivity of the four gages in WY2008 was 630 MJ ha^{-1} mm hr^{-1} (s.d. = 90 MJ ha^{-1} mm hr^{-1}).

In WY2009 the annual precipitation at Auberry was 526 mm, or 86% of the mean. Mean precipitation for the three functioning rain gages in José Basin was 554 mm, which was 35 mm more than at Auberry, but the values in José Basin were more variable than in WY2008 as the standard deviation was 139 mm. Again the measured precipitation in José Basin was not significantly correlated with elevation ($R^2 = 0.81$, $p = 0.29$). The mean erosivity in WY2009 was 390 MJ ha^{-1} mm hr^{-1} (s.d. = 210 MJ ha^{-1} mm hr^{-1}), or 38% less than the value in WY2008. There was no significant difference in annual precipitation between WY2008 and WY2009 ($p = 0.66$), but annual erosivity in WY2008 was significantly lower than the WY2009 value ($p = 0.09$).

Providence Creek and Bull Creek watersheds, KREW

Precipitation in the KREW watersheds falls largely as snow, although there can be summer rain storms as well as rain-on-snow events. The mean annual precipitation for the four KREW stations is 1240 mm per year (Korte and MacDonald, 2007), or more than double the mean value for the Auberry station. In WY2008 the Providence Creek watersheds received 83% of the mean annual precipitation, as compared to annual precipitation measuring 75% of the mean value at Auberry. Total precipitation was only 913 mm at the lowest gage, while the other three gages all had very similar totals of 1116 to 1148 mm, regardless of elevation (Figure 2.9). Annual precipitation was assumed to be directly correlated with elevation in both the Providence Creek and the Bull Creek watersheds in WY2008.

In WY2009 the mean precipitation at the Providence Creek rain gages was 962 mm (s.d. = 6 mm), or 78% of the mean annual precipitation for KREW (Figure 2.9). Precipitation at the upper Bull Creek rain gage was 1081 mm, which was only 12% more than the mean precipitation in the Providence Creek watersheds. Again, a direct correlation was assumed between annual precipitation and elevation in the Providence Creek watersheds. However, the lower Bull Creek precipitation gage did not collect sufficient data due to equipment malfunctions, and so it was assumed that all sediment fences in the Bull Creek watersheds received the same precipitation as the Upper Bull Creek rain gage.

2.5.2. Hillslope characteristics and sediment production

José Basin

The mean contributing area of the ten hillslopes with sediment fences in José Basin was 0.42 ha, but the standard deviation was relatively large at 0.32 ha (Table 2.8, Appendix A). The mean elevation of the ten sediment fences was 1100 m (s.d. = 107 m), and values ranged from 947 m to 1225 m. The hillslope surface areas were typically well covered, as litter covered more than half of the ground surface (mean = 56%, s.d. = 11%), while live vegetation averaged 25% (s.d. = 12%) and woody debris averaged 13% (s.d. = 7%). Percent bare soil and rock accounted for only 4% and 2% of the surface on average, respectively. Seven hillslopes were classified as other soil types and only three hillslopes were in Holland soil. Hillslopes in Holland soils and other soil types were not significantly different in area, slope, or surface cover.

Mean hillslope sediment production in José Basin was 7.4 x 10^{-3} kg m^{-2} (s.d. = 2.1 x 10^{-2} kg m^{-2}) in WY2008 (Table 2.8). The mean sediment production rate for the three hillslopes in Holland soil was only 6.7 x 10^{-5} kg m^{-2} (s.d. = 9.4 x 10^{-5} kg m^{-2}), or more than three orders of magnitude lower than the mean rate for other soil types (1.1 x 10^{-2} kg m^{-2}, s.d. = 2.5 x 10^{-2} kg m^{-2}) (Appendix A). The latter value was highly skewed by the sediment production rate for one hillslope, JHS10, which was an order of magnitude higher than any other hillslope. The relatively high variability and small number of hillslopes on Holland soil meant that there was no significant difference in hillslope sediment production rates with soil type ($p = 0.50$). In WY2009 no sediment was produced from any of the hillslopes in José Basin, which exemplifies the large potential interannual variability of hillslope sediment production as well as the typically low erosion rates found in forests with high percent surface cover.

Providence Creek and Bull Creek watersheds, KREW

The mean elevation of the hillslope sediment fences in the Providence Creek watersheds was 1915 m (s.d. = 54 m) (Appendix B), or 815 m higher than the mean elevation of the hillslope fences in José Basin, while the hillslope sediment fences in the Bull Creek watersheds had a mean elevation of 2320 m (s.d. = 131 m) (Appendix C). The mean area of the monitored hillslopes in the Providence Creek watersheds was 0.55 ha (s.d. = 0.37 ha), which was only slightly larger than the mean area for hillslopes in José Basin. However, the mean area for the monitored hillslopes in the Bull Creek watersheds was nearly four times the mean value for the Providence Creek hillslopes ($p < 0.0001$).

In WY2008 the mean sediment production rate for the ten hillslopes in the Providence Creek watershed was 7.9×10^{-4} kg m^{-2} (s.d. = 1.0×10^{-3} kg m^{-2}) (Appendix B), which was an order of magnitude lower than the mean value in José Basin. The mean sediment production rate for the four hillslopes in the Bull Creek watersheds was 58% of the value from the Providence Creek watersheds, but this difference was not significant ($p = 0.43$) (Appendix C). There was no significant difference in hillslope sediment production between José Basin and either the Providence Creek or the Bull Creek watersheds in WY2008 ($p \geq 0.33$).

In WY2009 the mean hillslope sediment production rate in the Providence Creek watersheds was 7.0×10^{-6} kg m^{-2} (s.d. = 2.2×10^{-5} kg m^{-2}), which was two orders of magnitude lower than the value the previous year. The mean value in the Bull Creek watersheds was 54 times the mean value for the Providence Creek watersheds, but this difference was not significant ($p = 0.23$) (Table 2.8). The high mean value for the Bull Creek hillslopes was largely due to one hillslope, BH1, which produced 2.5×10^{-3} kg m^{-2}, and was one of only two hillslopes in the Bull Creek watersheds that produced sediment in WY2009. Similarly to WY2008, there was no significant difference in sediment production between hillslopes in José Basin and hillslopes in either the Providence Creek or the Bull Creek watersheds in WY2009 ($p \geq 0.22$).

2.5.3. Road segment characteristics and sediment production

José Basin

Native surface roads accounted for 7.2 km or 66% of the surveyed road length. The mean length of the 133 native surface segments was 82 m, but this varied widely with a standard deviation of 124 m. The median value of 51 m is perhaps a better representation of the native surface segments in José Basin, as the mean value was skewed by the longest segment, which was 1.2 kilometers long. When weighted by length, the mean width of the native surface roads in José Basin was 2.5 m (s.d. = 0.5 m). The mean length-weighted slope was 8% (s.d. = 4%). Seventy-six percent of the segments were planar, and 21% were a combination of planar, outsloped with a berm, and insloped. The remaining segments were outsloped with a berm. The majority of the segments (65%) had either waterbars or dips as the main drainage feature, and none of the segments had diffuse drainage. Three of the native surface segments had stream crossings across road surface. Twenty-nine percent of the native surface road length had fillslope erosion at the drainage point. Of the 10.8 km, 1.4 km did not have any waterbars or dips as part of their drainage system. Of the remaining 9.4 km, 51% of the road length had effective waterbars or dips, while the remaining 49% had ineffective waterbars or dips. There were a total of 77 ineffective bars or dips on the 10.8 km of road, for a total of seven ineffective bars or dips per kilometer of native surface road.

Segments were mostly bare, as the mean surface cover due to gravel, litter, or vegetation was only 8% (s.d. = 14%). Forty-one percent of the surveyed road length had little to no traffic, while 26% was classified as having low traffic, and 33% was classified as having medium traffic. Thirty-eight percent of the surveyed road length was on Holland soil.

Rill erosion with a mean depth of at least five centimeters was observed on 45% of the native surface segments surveyed in José Basin. The mean segment length of the segments without rills was 61 m (s.d. = 50 m), while the value for segments with rills was nearly double at 116 m (s.d. = 114 m) ($p = 0.004$). The total rill length was 2.7 km, for an overall rill to road length ratio of 0.38. The mean rill length was 72 m (s.d. = 107 m) and the mean rill volume was 5.7 m^3 (s.d. = 13.7 m^3). The mean slope weighted by segment length for segments with rills was 10%, while the mean slope for segments without rills was only 4% ($p < 0.0001$).

The mean elevation of the 34 native surface road segments with sediment fences in José Basin was 1056 m (s.d. = 82 m), and the range was from 913 m to 1254 m. The native surface road segments with sediment fences in José Basin had a mean length of 44 m (s.d. = 16 m), which is 51% of the mean length of the surveyed segments ($p = 0.08$). This significant difference is not surprising given that the segments selected for monitoring are required to have a discrete top and bottom, and that very few of the monitored segments had broken waterbars in comparison to the surveyed segments.

The mean slope of the native surface segments with sediment fences in José Basin was 9% (s.d. = 3%), and the range was from 2% to 16%. The mean value of 9% is significantly higher than the mean slope of the surveyed segments ($p < 0.0001$). The much larger area but lower slope of the surveyed segments resulted in a mean area*slope factor that was only 17% larger than the segments with sediment fences ($p = 0.55$). The segments with sediment fences in José Basin averaged 30% (s.d. = 15%) surface cover or 70% bare soil, and this was significantly less bare soil than the surveyed segments ($p < 0.0001$). Only 5% of the monitored segments had very little to no traffic, while 52% were characterized as having a low amount of traffic. The remaining 43% had a medium traffic level.

In WY2008 the mean sediment production rate for the 12 native surface road segments in José Basin was 1.4 kg m^{-2} (s.d. = 2.3 kg m^{-2}) (Figure 2.10). Production rates varied widely, with the lowest rate occurring on JNO6 (0.042 kg m^{-2}) and the highest on JBT14 (7.9 kg m^{-2}). Relatively few segments produced the majority of the sediment, with 25% of the road length monitored producing 75% of the sediment (Figure 2.11).

In WY2009 the mean sediment production rate for the 29 native surface road segments in José Basin increased by 50% to 2.1 kg m^{-2} (s.d. = 3.1 kg m^{-2}) (Figure 2.10). Sediment production values varied by even more than in WY2008, as rates ranged from 0.0050 to 12.9 kg m^{-2}. This high variability helps explain why sediment production from native surface road segments was not significantly different between WY2008 and WY2009 despite the 50% increase ($p = 0.51$) (Figure 2.10). As in WY2009, relatively few segments produced large amounts of sediment in WY2009, with 25% of the road length monitored producing 75% of the sediment (Figure 2.11).

Stratification of the data by soil type showed that there were 21 road segments with sediment fences in Holland soil and 12 road segments in other soil types. The mean elevation of the Holland segments with sediment fences was 1109 m (s.d. = 66 m), while the mean value for the segments in other soil was 982 m (s.d. = 52 m) ($p < 0.0001$). However, elevation within José Basin was not significantly correlated to sediment production ($p = 0.92$). The mean length and area of segments were similar for both soil types, while the mean slope of the segments in Holland soil was 10% (s.d. = 3%) as compared to the mean value of 8% (s.d. = 3%) for the segments in other soil, and this difference was nearly significant ($p = 0.11$). The segments in Holland soil averaged 65% bare soil, which was significantly less than the mean of 79% for the segments in other soil types ($p = 0.0008$).

In WY2008 the mean sediment production rate for the five native surface segments in other soil types was 0.5 kg m^{-2} (s.d. = 0.7 kg m^{-2}) (Figure 2.12). Mean sediment production for the eight road segments in Holland soil averaged 1.9 kg m^{-2}, or nearly four times higher, but the standard deviation of 2.7 kg m^{-2} was 42% larger than the mean (Appendix D). The small sample sizes and high variability meant that road sediment production did not significantly differ by soil type for WY2008 ($p = 0.28$).

In WY2009 the mean sediment production rate for the 12 native surface segments in other soil types was 2.7 kg m^{-2} (s.d. = 4.1 kg m^{-2}), which was 5.4 times higher than in WY2008 ($p = 0.25$) (Figure 2.12). Almost half of this increase is due to JNO3, which produced 12.9 kg m^{-2} in WY2009. If this segment is excluded, the mean sediment production rate drops to 1.7 kg m^{-2} (s.d. = 2.4 kg m^{-2}), although this is still 3.4 times higher than the mean value from WY2008. The mean sediment production rate for the 18 road segments in Holland soil was 1.6 kg m^{-2} yr^{-1}, which was 16% lower than WY2008 (Figure 2.12). The explanation for the surprising contrast between the increase in sediment production from WY2008 to WY2009 for segments in other soil types as compared to the decrease in values for segments in Holland soil is unknown. As in WY2008, road sediment production in WY2009 was not significantly different by soil type ($p = 0.32$).

For the native surface segments in José Basin, sediment production was significantly correlated with segment slope ($R^2 = 0.11$; $p = 0.03$) (Figure 2.13). When sediment production was normalized by segment slope to account for the significantly steeper segments in Holland soil than in other soil types, the road segments on Holland soil still did not produce significantly more sediment than the road segments on other soil types for WY2008 or WY2009 ($p = 0.24$ and $p = 0.21$, respectively).

Providence Creek and Bull Creek watersheds, KREW

In the Providence Creek watersheds, the mean elevation of the six native surface road segments was 1859 (s.d. = 85 m), which is 800 m higher than the mean elevation of the native surface segments in José Basin. The mean area and slope of the segments with sediment fences in the Providence Creek watersheds generally were similar to the mean values in José Basin (Table 2.9). The main difference was that the native surface segments in the Providence Creek watersheds averaged only 48% bare soil (s.d. = 17%)

as compared to 70% in José Basin ($p < 0.0001$). The remaining 52% was comprised of 35% litter (s.d. = 22%), 10% gravel (s.d. = 10%), and 7% live vegetation (s.d. = 6%).

In WY2008 the mean sediment production rate for the six native surface road segments in the Providence Creek watersheds was 0.12 kg m^{-2} (s.d. = 0.14 kg m^{-2}) (Figure 2.10; Appendix E), and ranged over an order of magnitude from 0.01 to 0.4 kg m^{-2}. The mean rate was an order of magnitude lower than mean rate from native surface segments in José Basin, but the mean rates were not significantly different ($p = 0.22$) due to the high variability between segments.

The mean value of 0.14 kg m^{-2} (s.d. = 0.12 kg m^{-2}) in WY2009 was very similar to the previous year (Figure 2.10). Similar to WY2008, the mean value in the Providence Creek watersheds was only 7% of the mean rate in José Basin. However, again due to high variability, there was no significant difference between values in the Providence Creek watersheds and José Basin ($p = 0.14$).

In the Bull Creek watersheds, the mean elevation of the nine native surface road segments was 2292 m (s.d. = 62 m), 433 m higher than the mean elevation in the Providence Creek watersheds. The mean length was 57 m (s.d. = 25 m), and this was significantly longer than the mean segment length in José Basin ($p = 0.01$) and nearly significantly longer than the mean segment length in the Providence Creek watersheds ($p = 0.12$). Mean segment slope in the Bull Creek watersheds was 9% (s.d. = 3%), which is similar to the values in both José Basin and the Providence Creek watersheds. Percent bare soil for the native surface segments in the Bull Creek watersheds averaged 53% (s.d. = 21%), which was similar to the mean value in the Providence Creek watersheds. However, the mean gravel cover of 7% (s.d. = 5%) was significantly more than the mean value of 2% in the Providence Creek watersheds (s.d. = 1%) (p = 0.001) and nearly significantly more than the mean gravel cover of 4% in José Basin (s.d. = 8%) (p = 0.11).

The mean road sediment production rate in the Bull Creek watersheds was 0.042 kg m^{-2} (s.d. = 0.067 kg m^{-2}) in WY2008 (Appendix F), or 35% of the mean value from the Providence Creek watersheds and only 3% of the mean value from José Basin. The differences between road sediment production in the Bull Creek watersheds and the Providence Creek watersheds and José Basin were nearly significant in WY2008 at p = 0.19 and p = 0.11, respectively.

In WY2009 the mean sediment production rate for native surface road segments in the Bull Creek watersheds was 0.23 kg m^{-2} (s.d. = 0.27 kg m^{-2}), which was 5.5 times the value from WY2008; this increase was nearly identical to the increase for the hillslope sediment fences in the Bull Creek watersheds in WY2009. Unlike the previous year, road sediment production in the Bull Creek watersheds in WY2009 was 38% greater than in the Providence Creek watersheds, though this difference was not significant (p = 0.48). The mean road sediment production of 0.23 kg m^{2} in the Bull Creek watersheds was only 9% of the mean value for José Basin, and this difference was significant (p = 0.09).

2.5.4. Road sediment delivery

José Basin

Forty-five percent of the 7.2 km of surveyed native surface road length or 42% of the segments had no visible drainage feature (Figure 2.14). Sediment plumes accounted for the majority of the drainage features, although occasionally there was a drainage rill.

Drainage features tended to be relatively short, as only seven of the 57 segments, or 16% of the road length, had drainage features greater than 20 m long. The longest drainage feature in José Basin was 105 m long, and this came from a 246 m long segment.

Forty-six percent of the native surface road length in José Basin had a connectivity class of one, while 30% of the road length was directly connected to the stream network (Figure 2.15). The relatively high connectivity given the average plume length of only 16 m can be explained by the proximity of many roads to the stream channel. Of the 14 surveyed segments that were connected to a stream, seven segments or 500 m of road had plume lengths of zero meters, as the discharge points were directly into a stream.

The effect of soil type on sediment delivery was evaluated from the detailed data for 38 road segments prior to installing sediment fences. Thirteen of these segments were in other soil types, and 25 were on Holland soil. Twelve of the 13 segments in other soil types had a drainage feature, and the mean drainage feature length was 25 m (s.d. = 19 m) with a range of three to 60 m. Thirty percent of the road length on other soil types had a connectivity class of one, while 28% of the road length was connected to the stream (Figure 2.16).

Similarly to the segments in other soil types, only two of the 25 segments in Holland soil had no visible drainage features. Also similarly to segments in other soil types, the mean drainage feature length for segments in Holland soil was 27 m (s.d. = 17 m) and values ranged from six to 65 m. The similarities in plume length between segments in other soil types and segments in Holland soil indicate that native surface segments on Holland soil are no more likely to have a longer drainage feature than segments in other soil types. However, the percent of connected road length on Holland soil was 18%, which was slightly lower than the value for other soil types (Figure 2.16). This 10% difference is likely due to a higher proximity of other soil types to stream channels than Holland soils.

Providence Creek watersheds

In the Providence Creek watersheds, 27% of the 7.8 km of native surface road length had no visible drainage feature, and this is lower than the value of 45% for native surface segments in José Basin (Figure 2.14). However, only 3% of the native surface road length in the Providence Creek watersheds was directly connected to the stream network, which is only a tenth of the value for José Basin (Figure 2.15).

2.5.5. Modeling road sediment production and delivery in José Basin.

2.5.5.1. Predicting sediment production from native surface segments in José Basin

The univariate analysis showed that sediment production was significantly and positively correlated with segment slope, the length of rills on the segment, and the volume of rills on the segment (Table 2.10). Rill length was the most significant variable ($p = 0.0004$) and explained 39% of the variability in annual road sediment production.

The empirical multivariate model constructed using the survey data to predict sediment production from the native surface road segments in José Basin included rill length (R in m), area (A in m^2), percent Holland B horizon on the surface of the road segment (B), and annual precipitation (P in mm):

$$SP = 0.010 + 0.11*R - 0.016*A - 0.029*B + 0.0056*P \qquad \text{(equation 2.2)}$$

where SP equals the sediment production rate in kg m^{-2} yr^{-1} ($R = 0.59$) (Table 2.11). The model tended to over-estimate the lower sediment production rates and under-estimate the higher sediment production rates (Figure 2.17). The predicted sediment production rates from the multivariate model again confirm that relatively few segments typically produce a large amount of sediment, as only 12% of the segments were predicted to have sediment production rates greater than 4 kg m^{-2} yr^{-1}. The variables included did make physical sense except that sediment production decreased with increasing segment area.

Equation 2.2 could not be used to predict road sediment production for all the surveyed road segments because the surveys did not attempt to estimate the percent of Holland B horizon on the road surface. The simplified equation used to predict road sediment production from the surveyed native surface segments was:

$$SP = 0.010 - 0.016*A + 0.0056*P + 0.11*R \qquad \text{(equation 2.3),}$$

which has an R^2 of 0.49.

2.5.5.2. Total potential sediment produced and delivered from native surface segments in José Basin

The road survey showed that 42% of the 159 km of roads in José Basin were native surface, 18% were gravel surface, and 41% were paved. Mean annual precipitation for the seven gage-years of data in José Basin was 534 mm. Using the characteristics measured in the random survey and equation 2.3, the predicted mean sediment production rate for the 11 km of surveyed native surface roads in José Basin was 1.8 kg m^{-2} yr^{-1}. Given that there are an estimated 67 km of native surface roads in

José Basin, the estimated total sediment production is approximately 680 metric tons per water year, or 10 metric tons per kilometer of road length.

The road survey showed that 30% of the native surface road length in José Basin was directly connected to a stream. Multiplying this percentage by the estimated total sediment production indicates that up to 210 metric tons of sediment from native surface roads are being delivered each year to the stream network in José Basin.

2.5.5.3. Comparison of WEPP:Road predictions to measured values in José Basin

WEPP:Road poorly predicted sediment production rates for native surface road segments in José Basin ($R^2 = 0.03$, n = 43) (Figure 2.18). The general tendency was for WEPP:Road to under-predict annual sediment production, as the predicted sediment production rates were less than half of the measured values for 74% of the data. For 30% of the data the predicted sediment production rates were more than an order of magnitude lower than the observed values.

2.6. Discussion

2.6.1. Effects of climate on sediment production

The comparison of data between study sites provides a unique opportunity to evaluate the effect of elevation and climate on hillslope and road sediment production. There were no significant differences between hillslope sediment production rates in José Basin, the Providence Creek watersheds, or the Bull Creek watersheds in WY2008, and in WY2009 the highest elevation Bull Creek hillslopes produced the most sediment. The dense cover of vegetation and duff on the hillslopes protects the surface from rainsplash erosion and increases infiltration, reducing erosive overland flow. The ability of ground cover to minimize surface erosion rates applies whether the surface is in a rain or snow dominated area.

Roads are more susceptible to rainsplash detachment and erosive overland flow, and therefore have much higher sediment production rates than hillslopes. The lack of cover on a native road surface also makes the surface more susceptible to an increase in erosion with an increase in the ratio of rain to snow. Areas with much higher annual precipitation and annual erosivities generally have much higher road sediment production rates. On the Olympic Peninsula mean annual precipitation is 6.4 times the value in José Basin, and the mean sediment production rate was 41 Mg km^{-1} yr^{-1}, or four times the mean rate in José Basin (Table 2.12). The mean annual precipitation on St. John in the U.S. Virgin Islands is 1.5 to 2.3 times the value in José Basin, while road sediment production rates were 5-15 kg^{-2} m^{-2} yr^{-1} (Ramos-Scharrón and MacDonald, 2005) or 2.8 to 8.3 times the mean rate in José Basin (Table 2.12). The much higher erosion rates on St. John can be attributed to the annual erosivity on St. John being approximately 25 times higher than in José Basin (Ramos-Scharrón and MacDonald, 2005), and this indicates the potentially greater usefulness of erosivity for predicting erosion than total precipitation.

In northwestern California, the Jackson Demonstration State Forest receives approximately 1400 mm yr^{-1} of precipitation, which is twice the value for José Basin, but the annual erosivities are not as different (Renard et al., 1997). As the road sediment production rates of 0.5 to 4 kg m^{-2} yr^{-1} (Barrett and Tomberlin, 2006) were similar to values in José Basin, and this again indicates the greater utility of erosivity relative to total precipitation.

In the Sierra, like many areas, an increase in elevation typically increases the amount of snow relative to rain. This decreases the erosivity, as snowfall has minimal erosive energy, precipitation intensities are lower, and snowmelt rates are low in comparison to rainfall intensities, resulting in less overland flow. Hence road sediment production rates are typically lower in areas with snow or mixed snow-and-rain. Mean annual precipitation in the Providence Creek watersheds in WY2008 and WY2009 was approximately twice the value in José Basin, but due to the preponderance of snow, the annual erosivity was much lower. This explains why the mean sediment production rate in the Providence Creek watersheds for native surface roads was 0.13 kg m^{-2} yr^{-1} (s.d. = 0.13 kg m^{-2} yr^{-1}), or just 7% of the mean value in José Basin.

In the higher elevation Bull Creek watersheds the mean road sediment production rate in WY2008 was 35% of the value from the Providence Creek watersheds, while in WY2009 the mean road sediment production rate in the Bull Creek watersheds was 1.6 times the value in the Providence Creek watersheds. The higher sediment production in the Bull Creek watersheds in WY2009 can be attributed to a relatively rare localized summer rainstorm, which can drastically increase the annual erosivity.

Road sediment production rates in the Eldorado National Forest (ENF) (Figure 2.1), which has a mixed rain-on-snow climate, provide further insight into the role of elevation and climate on road sediment production. On the ENF annual precipitation was 2.5 times higher than in José Basin, but the study area was snow dominated and the mean road sediment production rate of 0.22 to 0.81 kg m^{-2} yr^{-1} (Coe, 2006) was only 12-45% of the mean value from José Basin. Similarly, annual precipitation in the Idaho batholith is approximately 720 mm, with 60% falling as snow, and the mean sediment production rate from native surface road segments was 0.48 kg m^{-2} yr^{-1} (Megahan, 1974). This is very similar to the mean value for the ENF but only 27% of the mean value from José Basin. The lower road sediment production rates on the ENF and the Idaho batholith can be explained by the lower erosivity due to the greater proportion of snow. These comparisons to other studies in rain, rain-on-snow, and snow dominated climates suggest that road sediment production varies with annual precipitation in rain dominated areas, but that annual erosivity is a much better predictor of road erosion rates when the precipitation is a mixture of rain and snow.

The exact effect of potential global climate change on the amount of precipitation in the Southern Sierra is uncertain, but overall global warming is a potential outcome (IPCC, 2007). Warmer temperatures will increase the rain to snow ratio in the southern Sierra and other mountainous areas. This warming will increase sediment production from native surface roads in the KREW watersheds, which will reduce the current 10-fold difference in mean sediment production rates between the mixed-climate Providence Creek watersheds and the rain dominated José Basin. The potential shift to more rain the Providence Creek watersheds also will likely increase sediment delivery by increasing the amount of runoff and erosion from native surface road segments. Similar increases can be expected in other areas that are at or just above the rain-snow boundary.

2.6.2. Assessing and reducing road sediment production in José Basin

A crude estimate of the relative importance of unpaved roads to total sediment production in José Basin can be made by comparing the estimated hillslope sediment yields to the sediment production and delivery from native surface roads. The mean sediment production rate for hillslopes in José Basin was only 0.0037 kg m^{-2} yr^{-1} (s.d. = 0.015 kg m^{-2} yr^{-1}). If this rate is multiplied by the area of the basin and 100% connectivity is assumed, the background sediment yield is 290 tons yr^{-1}. Road surveys and the multivariate road sediment production model predicted that native surface roads would generate 680 tons of sediment per year. Since 30% of the native surface road length is connected to a stream, native surface segments in José Basin could deliver up to 210 tons of sediment per year to the stream network. This is 72% of the estimated hillslope sediment yield, indicating that road erosion is a major contributor of sediment to streams in José Basin, especially since they occupy less than one percent of the land area.

Unpaved roads also have been identified as a major source of sediment in forested watersheds in other locations (Reid and Dunne, 1984; Swift, 1988; Bilby et al., 1989; Luce and Black, 1999; Ketcheson et al., 1999; Coe, 2006). On St. John, unpaved roads delivered more sediment to the streams than all of the natural sources, including bank erosion, treethrow, and erosion from undisturbed hillslopes (Ramos-Scharrón and MacDonald, 2005). In Australia unsealed roads and logging tracks were identified as the most hydrologically active areas within a logged forest, and these are often significant sediment sources (Croke and Hairsine, 2006). Because excessive sediment reduces water and habitat quality (Bilby et al., 1989; Ziegler and Giambelluca, 1997; Kolka and Smidt, 2004), forest managers need to consider means for reducing road sediment production and delivery.

The results presented in this study can help guide best management practices for reducing road sediment production and delivery in José Basin. The significant variables in the multivariate model for predicting sediment production from native surface road segments were rill length (m), annual precipitation (mm), segment area (m^2), and the percent Holland soil B horizon on the road surface (Table 2.11). The positive correlations of sediment production with rill length and annual precipitation make physical sense, and the former has direct implications for management. However, the negative coefficients for segment area and percent Holland soil B horizon merit further explanation.

In WY2008 and WY2009 rilled segments respectively produced ten and six times more sediment per unit area than unrilled segments when normalized by slope ($p < 0.0001$ and $p = 0.007$) (Figure 2.19). Other studies have shown that surface runoff can detach and transport more sediment once it is channeled into a rill (Meyer et al., 1975; Loch and Donnellan, 1983; Poesen, 1987). These results indicate that rills are a major source of sediment from native surface road segments relative to rainsplash and sheetwash erosion. Rilling readily occurs on native surface roads due to the depressions caused by tire tracks that concentrate the flow. The recognized management practice to reduce rilling and road sediment production is to restrict driving in wet conditions, and this study supports this practice.

An analysis of the segments with rills versus segments without rills also can be used to pinpoint where rills are most likely to form, and hence when waterbars or the application of gravel could help minimize rilling. The mean segment area for rilled segments was 130 m^2 (s.d. = 50 m^2) as compared to 100 m^2 (s.d. = 40 m^2) for segments without rills. This was significant at $p = 0.07$, indicating that rills form on longer or wider segments. Rilled and unrilled segments were more clearly separated by the product of road segment area times segment slope, as the area*slope factor for rilled roads averaged 1330 $m^2\ m\ m^{-1}$ (s.d. = 560 $m^2\ m\ m^{-1}$) as compared to only 880 $m^2\ m\ m^{-1}$ (s.d. = 560 $m^2\ m\ m^{-1}$) for unrilled segments ($p = 0.02$). This indicates that larger, steeper segments should be broken into smaller segments by installing waterbars when the area*slope factor exceeds about 1000 $m^2\ m\ m^{-1}$.

Segment slope was a significant continuous variable in the univariate analysis, but the R^2 was low and slope was not a significant variable in the multivariate model for predicting road sediment production. Figure 2.13 suggests a simple categorical classification of sediment production versus slope, and Figure 2.20 shows that mean sediment production for segments with slopes greater than 7% was an order of magnitude higher than for segments with slopes less than 7% ($p = 0.18$ and 0.06 for WY2008 and WY2009, respectively). This indicates that management practices to reduce sediment production, such as graveling or installing waterbars, should focus on road segments that are steeper than 7%.

The multivariate model predicted that road sediment production in José Basin is significantly correlated to annual precipitation ($p = 0.06$). Other studies also have shown that annual precipitation, or more importantly annual erosivity, is a significant variable in predicting road sediment production (Ramos-Scharrón and MacDonald, 2005; Coe, 2006; Sugden and Woods, 2007; Welsh, 2008; Fu et al., 2010). This study shows that management practices to reduce road sediment production are much more important in rain dominated areas.

The multivariate model predicts a decrease in sediment production with increasing segment area, which is counter-intuitive. However, this can be explained by the greater potential for sediment deposition on many of the larger segments. For segments with areas greater than 150 m^2, the mean slope of the bottom ten meters averaged 6% (s.d. = 2%) as compared to 8% (s.d. = 3%) for the segments with areas less than 100 m^2, and this difference was significant at $p = 0.04$. Road segments with slopes less than 7% were already shown to have lower sediment production rates than segments steeper than 7%. These results indicate that the flatter sections at the ends of the longer segments can act as depositional areas, and this can explain the negative correlation between segment area and sediment production in the multivariate model.

The multivariate model also predicts a decrease in sediment production with an increasing percent Holland B horizon on the road surface, but this is most likely a statistical artifact. As previously described, the Holland B horizon is a highly erodible layer, and in theory sediment production should increase with an increase in the percent B horizon. However, the univariate analysis did not find any correlation between sediment production and the percent B horizon, and there was no significant difference in sediment production between roads in Holland soil and roads in other soil types. According to the data gathered in this study, there is no clear justification for focusing road sediment reduction efforts on Holland soils.

The very large variability in sediment production rates between sites makes it inefficient to universally apply management practices to reduce road sediment production, as just a few segments often account for most of the road-related sediment being delivered to the stream network. For example, segment JNO3 in José Basin had a sediment production rate of 12.9 kg m^2 yr^{-1} in WY2009, which was nearly an order of magnitude more than any of the other segments in either water year. JNO3 had an extensive rill system, with 53 m of rills on a 35 m long segment, giving it a higher rill density than any other segment, and it had a moderate to high delivery potential. A best management practice to reduce sediment contributions from native surface road segments should begin with pinpointing the “trouble” segments and road sections that are apt to deliver the most sediment to the stream network. The data collected in this thesis indicate that management efforts should focus on those segments with extensive rill erosion, segments with area*slope factors greater than 1000 m^2 m m^{-1}, and segments with slopes greater than 7%. Sediment production on these segments can be reduced through graveling or paving as examined in the next chapter. Sediment delivery can be reduced by installing waterbars that direct flow away from streams, which also will be examined in more detail in the following chapter.

2.7. Conclusions

This project monitored hillslope and road sediment production in the low elevation José Basin (800-1200 m), the mid-elevation Providence Creek watersheds (1485-2005 m), and the upper elevation Bull Creek watersheds (2050-2420 m) in the Sierra National Forest, California in WY2008 and WY2009. The mean hillslope sediment production rate in José Basin in WY2008 was 7.4×10^{-3} kg m^{-2}. While sediment production rates for hillslopes in the Providence Creek and Bull Creek watersheds were at least an order of magnitude less than values from José Basin in WY2008, there was no significant difference in values between the three areas. In WY2009 none of the hillslopes in José Basin produced any sediment, and rates in the Bull Creek watersheds were higher than values in the Providence Creek watersheds. According to these data, sediment production from hillslopes was not significantly higher in rain dominated areas than snow dominated areas, and this can be attributed to the dense cover of vegetation and litter protecting the hillslope from rainsplash and erosive overland flow.

The mean road sediment production rate in José Basin was 1.8 kg m^{-2} yr^{-1}, with values from individual segments ranging from zero to 12.9 kg m^{-2} yr^{-1}. There was no significant difference in road sediment production between hillslopes and road segments in Holland soils and in other soil types. Thirty percent of the native surface road length in José Basin was directly connected to the stream network.

While WEPP:Road performed poorly in predicting sediment production from native surface roads in José Basin, an empirical multivariate model predicted road sediment production to increase with increasing in annual precipitation and total rill length on the road surface, and decrease with an increase in road segment area. Using this model, native surface roads in José Basin are estimated to produce 680 tons yr^{-1} of sediment, and up to 210 tons yr^{-1} are delivered to the stream network. In contrast, hillslopes, which occupy orders of magnitude more area than roads, are estimated to contribute 290 tons yr^{-1}. This indicates that native surface roads are a major contributor of sediment in José Basin.

Mean road sediment production in the Providence Creek watersheds was 0.13 kg m^{-2} yr^{-1}, which was more than an order of magnitude lower than in José Basin. Only 3% of the road length was connected to a stream, so road sediment delivery to streams is very low. Mean road sediment production in the Bull Creek watersheds was similar to the values from the Providence Creek watersheds. The results show that road sediment production is much higher in rain dominated areas than in snow dominated areas, as the bare surface subjected to rainsplash and higher rates of overland flow. Road sediment production rates in the Providence Creek watersheds would likely experience a ten-fold increase if the dominant precipitation were to switch from snow to rain.

Road sediment production was proportional to the total length of rills on a segment, indicating the importance of rilling for road sediment production. An important management implication is to restrict driving during wet conditions to reduce tire depressions, which in turn can reduce rilling and sediment production. Rilling was more extensive on longer, steeper segments, and erosion control efforts and best management practices should target these segments. Practices that aim to reduce sediment production and delivery such as graveling, paving, grading, and installing waterbars are examined in the following chapter.

2.8. Literature cited

Anderson, D.M., and L.H. MacDonald. 1998. Modeling road surface sediment production using a vector geographic information system. *Earth Surface Processes and Landforms* **23**: 95-107.

Barrett, B., and D. Tomberlin. 2006. Sediment production on forest road surfaces in California's Redwood region: results for HY2006 and HY2007. California Board of Forestry and Fire Protection-Monitoring Study Group Meeting, February 13, 2008, Redding, CA, USA.

Beechie, T.J., C.N. Veldhuisen, E.M. Beamer, D.E. Schuett-Hames, R.H. Conrad, P. DeVries. 2005. Monitoring treatments to reduce sediment and hydrologic effects from roads. In: *Monitoring Stream and Watershed Restoration*, Roni, R. (ed). America Fisheries Society, Bethesda, MD. Pp. 35-65.

Ben-dor, E., and A. Banin. 1989. Determination of organic matter content in arid-zone soils using a simple loss-on-ignition method. *Communications in Soil Science and Plant Analysis* **20(15-16):** 1675-1695.

Bilby, R.E., K. Sullivan, and S.H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds of south-western Washington. *Forest Science* **35**: 453-468.

Bowling, L.C., and D.P. Lettenmaier. 2001. The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. In: *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas.* Wigmosta, M., and S. Burges (eds.). Water Science and Application 2. American Geophysical Union, Washington, DC, USA. Pp. 145-164.

Brakensiek, D.L., H.B. Osborn, and W.J. Rawls. 1979. Field manual for research in agricultural hydrology. U.S. Department of Agriculture, Agriculture Handbook 224. 73 pp.

Brown, T.C., and D. Binkley. 1994. Effect of management on water quality in North American forests. USDA Forest Service GTR-RM-248, Fort Collins, CO, USA. 27 pp.

Brunton, D.A., and R.B. Bryan. 2000. Rill network development and sediment budgets. *Earth Surface Processes and Landforms* **25**: 783-800.

Cafferata, P.H., D.B.R. Coe, and R.R. Harris. 2007. Water resource issues and solutions for forest roads in California. In: *Integrated watershed management: Partnerships in science, technology, and planning*. Proceedings of the American Institute of Hydrology Annual Meeting and International Conference, Reno, NV, USA. 18 pp.

California Department of Water Resources. 2010. California Data Exchange Center <http://cedec.water.ca.gov>. Accessed January 2010.

Cederholm, C.J., L.M. Reid, and E.O. Salo. 1981. Cumulative effects of logging road sediment on salmonids populations in the Clearwater River, Jefferson County, Washington. In: *Salmon-Spawning Gravel: A Renewable Resource in the Pacific Northwest?* Washington Water Research Center, Pullman, WA, USA. Pp. 38-74.

Chappell, N.A., P. McKenna, K. Bidin, I. Douglas, and R.P.D. Walsh. 1999. Parsimonious modeling of water and suspended sediment flux from nested catchments affected by selective tropical forestry. *Philosophical Transactions of the Royal Society: Biological Sciences.* **354**: 1831-1846.

Coe, D. 2006. Sediment production and delivery from forest roads in the Sierra Nevada, California. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 107 pp.

Croke, J.C., and P.B. Hairsine. 2006. Sediment delivery in managed forests: A review. *Environmental Review* **14**: 59-87.

Croke, J., and S. Mockler. 2001. Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms* **26**: 205-217.

Croke, J., S. Mockler, P. Fogarty, and I. Takken. 2005. Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. *Geomorphology* **68**: 257-268.

Dunne, T., and L. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman and Co., New York, NY, USA.

EPA, 2010. What is sediment pollution? United States Environmental Protection Agency. <www.epa.gov/owow_keep/NPS/toolbox/other/KSMO_Sediment.pdf>.

Fu, B., L.T.H. Newham, and C.E. Ramos-Scharrón. 2010. A review of surface erosion and sediment delivery models for unsealed roads. *Environmental Modeling & Software* **25**: 1-14.

Gardner, W.H. 1986. Water Content. In: *Methods of Soil Analysis Part I: Physical and Mineralogical Methods.* Klute A. (ed.). Agronomy Series, No. 9, pt. 1. American Society of Agronomy, Madison, WI, USA. Pp. 493-544.

Harr, R.D., and R.A. Nichols. 1993. Stabilizing forest roads to help restore fish habitats: A Northwest Washington example. *Fisheries* **18(4)**:18-22.

Intergovernmental Panel on Climate Change. 2007. Fourth assessment report: Climate change 2007. <http://www.ipcc.ch/>. Accessed March 2010.

Ketcheson, G.L., W.F. Megahan, and J.G. King. 1999. “R1-R4” and “BOISED” sediment prediction model tests using forest roads in granitics. *Journal of American Water Resources Association* **35(1)**: 83-98.

Kolka, R.K., and M.F. Smidt. 2004. Effects of forest road amelioration techniques on soil bulk density, surface runoff, sediment transport, soil moisture, and seedling growth. *Forest Ecology and Management* **202**: 313-323.

Korte, A. In preparation. Road sediment production and delivery in the Sierra Nevada. M.S. thesis, Colorado State University, Fort Collins, CO, USA.

Korte, A., and L.H. MacDonald. 2007. Measuring and predicting road sediment production and watershed-scale sediment delivery. Presentation at Colorado State University Hydrology Days, Fort Collins, CO, USA.

Lal, R. 1988. Erodibility and erosivity. In: *Soil Erosion Research Methods*. Lal, R. (ed.). Soil and Water Conservation Society, Ankeny, IA, USA. Pp.141-160.

LaMarche, J.L., and D.P. Lettenmaier. 2001. Effects of flood flows on forest roads. *Earth Surface Processes and Landforms* **26(2)**: 115-134.

Lane, P.N.J., P.B. Hairsine, J.C. Croke, and I. Takken. 2006. Quantifying diffuse pathways for overland flow between the roads and streams of the Mountain Ash forests of central Victoria Australia. *Hydrological Processes* **20**: 1875-1884.

Leopold, L.B., M.G. Wolman, and T.P. Miller. 1964. Fluvial Processes in Geomorphology, Freeman, San Francisco, CA, USA. 522 pp.

Loch, R.J., and T.E. Donnellan. 1983. Field simulator studies on two clay soils of Darling Downs, Queensland. I. The effect of plot length and tillage orientation on erosion processes and runoff and erosion rates. *Australian Journal of Soil Resources* **21**: 33-46.

Luce, C.H., and T.A. Black. 1999. Sediment production from forest roads in western Oregon. *Water Resources Research* **35(8)**: 2561-2570.

Luce, C.H. and T.W. Cundy. 1994. Parameter identification for a runoff model for forest roads. *Water Resources Research* **30(4)**: 1057-1069.

MacDonald, L.H., D. Coe, and S. Litschert. 2004. Assessing cumulative watershed effects in the central Sierra Nevada: Hillslope measurements and catchment-scale modeling. In: *Proceedings of the Sierra Science Symposium*. Murphy, D.D., and P.A. Stine (eds.). USDA Forest Service General Technical Report, PSW GTR-193, pp. 149-158.

MacDonald, L.H., R.W. Sampson, and D.M. Anderson. 2001. Runoff and road erosion at the plot and road segment scale, St. John, U.S. Virgin Islands. *Earth Surface Processes and Landforms* **26**: 1-22.

Megahan, W.F. 1974. Erosion over time: A model. Research paper INT-156, USDA Forest Service, Ogden, UT, USA. 14 pp.

Megahan, W.F., and G.L. Ketcheson. 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. *Water Resources Bulletin* **32(2)**: 371-382.

Merz, W., and R.B. Bryan. 1993. Critical conditions for rill initiation on sandy loam brunisols: Laboratory and field experiments in southern Ontario, Canada. *Geoderma* **57**: 357-385.

Meyer, L.D., G.R. Foster, and S. Nikolov. 1975. Effect of flow rate and canopy cover on rill erosion. *Transactions of the American Society of Agricultural Engineering* **18**: 905-911.

Minear, J.T., and G.M. Kondolf. 2009. Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California. *Water Resources Research* **45.** 8 pp.

Montgomery, D.R. 1994. Road surface drainage, channel initiation, and slope instability. *Water Resources Research* **30(6)**: 1925-1932.

Petkovšek, G. 2001. RF - A tool for calculation of RUSLE R-factor.
<http://ksh.fgg.uni-lj.si/KSH_ANG/introduction/gregor/rf.htm.>

Pietraszek, J. 2006. Controls on post-fire erosion at the hillslope scale, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 124 pp.

Poesen, J. 1987. Transport of rock fragments by rill flow—a field study. In: *Rill Erosion: Processes and Significance*. R.B. Bryan (ed.). *Catena Supplemental* **8**: 35-54.

Ramos-Scharrón, C.E., and L.H. MacDonald. 2005. Measurement and prediction of sediment production from unpaved roads, St. John, U.S. Virgin Islands. *Earth Surface Processes and Landforms* **30**: 1283-1304.

Ramos-Scharrón, C.E., and L.H. MacDonald. 2007. Runoff and suspended sediment yields from an unpaved road segment, St. John, US Virgin Islands. *Hydrological Processes* **21(1)**: 35-50.

Reid, L.M., and T. Dunne. 1984. Sediment production from forest road surfaces. *Water Resources Research* **20(11)**: 1753-1761.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997.

Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agricultural Handbook No 703, Washington, D.C. 324 pp.

Robichaud, P.R., and R.E. Brown. 2002. Silt fences: An economical technique for measuring hillslope soil erosion. USDA Forest Service, General Technical Report RMRS-GTR-94. Fort Collins, CO, USA. 24 pp.

Sugden, B.D., and S.W. Woods. 2007. Sediment production from forest roads in Western Montana. *Journal of the American Water Resources Association* **43(1)**: 193-206.

Swift Jr., L.W. 1988. Forest access roads: Design, maintenance, and soil loss. In: *Forest Hydrology and Ecology at Coweeta.* Swank, W.T., and D.A. Crosley, Jr. (eds.), Springer-Verlag, New York, USA. Pp. 313-324.

Tagart, J.V. 1976. The survival from egg deposition to emergence of Coho salmon in the Clearwater River, Jefferson County, Washington. M.S. thesis, University of Washington, Seattle, WA, USA. 101 pp.

USDA Forest Service. 1983. Soil survey of Sierra National Forest area, California. USDA Forest Service, Pacific Southwest Region: Auberry, Cascadel Point, Musick Mtn., and Shaver Lake Quadrangles. 1:24,000. 7.5 Minute Series.

Weaver, W., and D. Hagans. 1999. Storm-proofing forest roads. In: *Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium*, OSU Department of Forest Engineering and International Union of Forestry Research Organizations, Corvallis, OR, USA. Pp. 230-245.

Welsh, M.J. 2008. Sediment production and delivery from forest roads and off-highway vehicle trails in the upper South Platte River watershed, Colorado. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 154 pp.

Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. *Water Resources Bulletin* **32**: 1195-1207.

Ziegler, A.D., and T.W. Giambelluca. 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. *Journal of Hydrology* **196**: 204-229.

Ziegler, A.D., T.W. Giambelluca, R.A. Sutherland, M.A. Nullet, S. Yarnasarn, J. Pinthong, P. Preechapanya, and S. Jaiarree. 2004. Toward understanding the cumulative impacts of roads in upland agricultural watersheds of northern Thailand. *Agricultural Ecosystem Environments* **104**: 145-158.

Ziegler, A.D., R.A. Sutherland, and T.W. Giambelluca. 2000. Partitioning total erosion on unpaved roads into splash and hydraulic components: The roles of interstorm surface preparation and dynamic erodibility. *Water Resources Research* **36(9)**: 2787-2791.

2.9. Tables

Table 2.1. Elevations and annual precipitation for WY2008 and WY2009 for the four climate stations in the KREW watersheds. There are no data for the lower Bull Creek rain gage in WY2009.

		Annual precipitation (mm)	
Climate station	**Elevation (m)**	**WY2008**	**WY2009**
Lower Providence	1749	913	966
Upper Providence	1984	1148	958
Lower Bull	2194	1116	-- --
Upper Bull	2463	1133	1081
Mean (s.d.)	**2098 (304)**	**1078 (110)**	**1002 (69)**

Table 2.2. Hillslope characteristics and surface cover categories measured for each hillslope with a sediment fence in José Basin. The O horizon depth was measured at nine systematically-spaced points on each hillslope.

Hillslope characteristics	**Hillslope surface cover categories**
Dominant soil type *(Holland, other)*	Bare soil
Area *(m^2)*	Litter
Axis length *(m)*	Woody debris (>1 cm diameter)
Axis gradient *(%)*	Live vegetation
Mean right and left sideslope gradients *(%)*	Rock (>1 cm diameter)
Presence of rills *(Y/N)*	Bedrock
Total rill length *(m)*	
Mean rill width *(m)*	
Mean rill depth *(m)*	
Shortest distance from rill to fence *(m)*	
O horizon depth *(m)*	

Table 2.3. Number of hillslopes and native surface road segments with valid sediment production data in Holland soil and other soil types in José Basin for WY2008 and WY2009.

	Hillslopes		**Native surface road segments**	
Water year	Other soil types	Holland soil	Other soil types	Holland soil
2008	7	3	5	8
2009	7	3	12	18
Totals	**14**	**6**	**17**	**26**

Table 2.4. Number of hillslopes and native surface road segments with valid sediment production data in the Providence Creek and Bull Creek watersheds from WY2004 through WY2009.

	Providence Creek watersheds		**Bull Creek watersheds**	
Water year	Hillslopes	Native surface segments	Hillslopes	Native surface segments
2008	10	6	6	9
2009	10	6	6	9
Totals	**59**	**55**	**34**	**45**

Table 2.5. Road segment characteristics measured, estimated, or observed for each segment with a sediment fence and the surveyed road segments. "/E" indicates that the characteristic was estimated rather than measured for the segments that were not monitored for sediment production.

Characteristic	**Measured (M), estimated (E), or observed (O)**	**Continuous variable (C) or categorical group (G)**	**Method of measurement**
Segment length *(m)*	M	C	Meter wheel
Surface type *(Native, gravel)*	O	G	
Active width *(m)*	M	C	Cloth tape
Total width *(m)*	M	C	Cloth tape
Segment slope *(%)*	M	C	Clinometer
Bare soil *(%)*	M / E	C	Cover count
Gravel cover *(%)*	M / E	C	Cover count
Traffic level *(Very low, low, medium)*	E	G	
Evidence of past surface rocking *(Y/N)*	O	G	
Cutslope height *(m)*	E	C	
Cutslope gradient *(%)*	M	C	Clinometer
Cutslope percent bare soil *(%)*	E	C	
Slope of upper hillslope *(%)*	M	C	Clinometer
Slope of lower hillslope *(%)*	M	C	Clinometer
Ditch width *(m)*	M	C	Cloth tape
Ditch slope *(%)*	M	C	Clinometer
Maximum rill length *(m)*	M	C	Cloth tape
Mean rill width *(m)*	M	C	Ruler
Mean rill depth *(m)*	M	C	Ruler
Drain type *(see Table 2.6)*	O	G	
Drain feature *(see Table 2.6)*	O	G	
Drain armoring *(Y/N)*	O	G	
Water cross armoring *(Y/N)*	O	G	
Armoring buried *(Y/N)*	O	G	
Armoring intact *(Y/N)*	O	G	
Pushout present *(Y/N)*	O	G	
Pushout effective *(Y/N)*	O	G	
Fillslope erosion *(Y/N)*	O	G	
Maximum fillslope rill depth *(m)*	M	C	Ruler
Multiple fillslope rills *(Y/N)*	O	G	
Drainage feature length *(m)*	M	C	Cloth tape
Drainage feature slope *(%)*	M	C	Clinometer
Drainage feature roughness *(1,2,3,4)*	O	C	
Connectivity class *(1,2,3,4)*	O	G	
Culvert present *(Y/N)*	O	G	
Culvert plugged *(%)*	E	C	
Scour at culvert outlet *(Y/N)*	O	G	
Volume of scour at culvert outlet *(m^3)*	M	C	Cloth tape

Table 2.6. Drain type and drain feature categories used to describe each road segment. Slashes indicate a mixture of types or features within a road segment. *Sediment production was not measured on segments that were either completely or partially outsloped or had any diffuse drainage.

Drain types	Drain features
Insloped	Diffuse*
Outsloped (diffuse)*	Dip
Outsloped (with a berm)	Pushout
Planar	Waterbar
Through cut	Stream crossing
Insloped/Planar	Cattle guard
Insloped/Outsloped with a berm	On segment deposition
Outsloped with a berm/Planar	Intersection
Planar/Outsloped*	Diffuse/Dip*
Insloped/Outsloped/Planar*	Diffuse/Waterbar*
	Diffuse/Pushout*
	Diffuse/Intersection*
	Diffuse/On segment deposition*
	Dip/Pushout
	Dip/On segment deposition
	Intersection/On segment deposition

Table 2.7. Definitions of connectivity classes and the associated potential for sediment to be delivered to the stream network.

Connectivity class	**Drainage characteristics**	**Potential for sediment delivery**
1	Drainage feature <10 m long.	Very low
2	Drainage feature <20 m long.	Low/moderate
3	Drainage feature >20 m long but more than 10 m from a stream channel.	Moderate/high
4	Drainage feature to within 10 m of a stream channel, regardless of length.	High

Table 2.8. Mean elevation, area, and sediment production rates for hillslopes in José Basin and the Providence Creek and Bull Creek watersheds for WY2008 and WY2009. None of the monitored hillslopes in José Basin produced sediment in WY2009.

					Mean sediment production rate (kg m^{-2} yr^{-1})					
Study site	**Elevation (m)**		**Area (ha)**		**WY2008**			**WY2009**		
	Mean	**s.d.**	**Mean**	**s.d.**	**n**	**Mean**	**s.d.**	**n**	**Mean**	**s.d.**
José Basin	1100	8104	0.42	0.32	10	7.4 x 10^{-3}	2.1 x 10^{-2}	10	0	0
Providence Creek watersheds	1915	54	0.55	0.37	10	7.9 x 10^{-4}	1.0 x 10^{-3}	11	7.0 x 10^{-6}	2.2 x 10^{-5}
Bull Creek watersheds	2320	131	2.08	0.84	4	4.6 x 10^{-4}	9.1 x 10^{-4}	7	3.8 x 10^{-4}	9.5 x 10^{-4}

Table 2.9. Mean elevation, area, slope, and sediment production rates for native surface road segments in José Basin and the Providence Creek and Bull Creek watersheds for WY2008 and WY2009.

							Mean sediment production rate (kg m^{-2} yr^{-1})					
	Elevation (m)		**Area (m^2)**		**Slope (m m^{-1})**		**WY2008**			**WY2009**		
Basin or watersheds	**Mean**	**s.d.**	**Mean**	**s.d.**	**Mean**	**s.d.**	**n**	**Mean**	**s.d.**	**n**	**Mean**	**s.d.**
José Basin	1056	82	115	44	9	3	12	1.4	2.3	29	2.1	3.1
Providence Creek watersheds	1859	85	102	36	10	3	6	0.12	0.14	6	0.14	0.12
Bull Creek watersheds	2292	62	117	48	9	3	9	0.042	0.067	9	0.23	0.27

Table 2.10. Correlation coefficients, coefficients of determination, and p-values for the site variables included in the univariate analysis of annual sediment production from native surface road segments in José Basin (n = 43). Values in bold are significant at $p \leq 0.10$.

Variable	**r**	**R^2**	**p-value**
Length (m)	-0.13	0.02	0.53
Area (m^2)	-0.14	0.02	0.65
Slope ($m\ m^{-1}$)	**0.30**	**0.09**	**0.03**
Area*Slope ($m^2 m\ m^{-1}$)	0.08	0.01	0.33
Annual precipitation (mm)	0.04	0.00	0.22
Annual erosivity (MJ ha^{-1} mm hr^{-1})	-0.01	0.00	0.35
Percent bare soil	0.27	0.07	0.15
Percent gravel cover	-0.09	0.01	0.26
Percent Holland soil B horizon	-0.10	0.01	0.72
Elevation (m)	-0.18	0.03	0.92
Rill length (m)	**0.62**	**0.39**	**0.0004**
Rill volume (m^3)	**0.49**	**0.24**	**0.0016**

Table 2.11. Coefficients and p-values for significant variables in the multivariate model for predicting annual sediment production from native surface road segments in José Basin.

Variable	**Coefficient**	**p-value**
Rill length (m)	0.11	<0.0001
Segment area (m^2)	- 0.016	0.02
Percent Holland soil B horizon on segment surface	- 0.029	0.03
Annual precipitation (mm)	0.0056	0.06
Intercept	0.010	

Table 2.12. Sediment production rates from five other studies in snow, mixed rain and snow, and rain climates. Data from the current study are in italics.

Dominant precipitation	Study	Annual precipitation	Annual sediment production from native surface roads	
		mm	kg m^{-2}	Mg km^{-1}
Snow	*Bull Creek watersheds*	1000	*0.13*	
Mixed rain and snow	*Providence Creek watersheds*	1100	*0.14*	
	Coe, 2006	1300	0.32	1.6
	Megahan, 1974	700	0.48	
Rain	*José Basin*	530	*1.8*	*10*
	Barrett and Tomberlin, 2006	1400	0.5 to 4	
	Ramos-Scharrón and MacDonald, 2005	900-1400	5 to 15	
	Reid and Dunne, 1984	3900		41

2.10. Figures

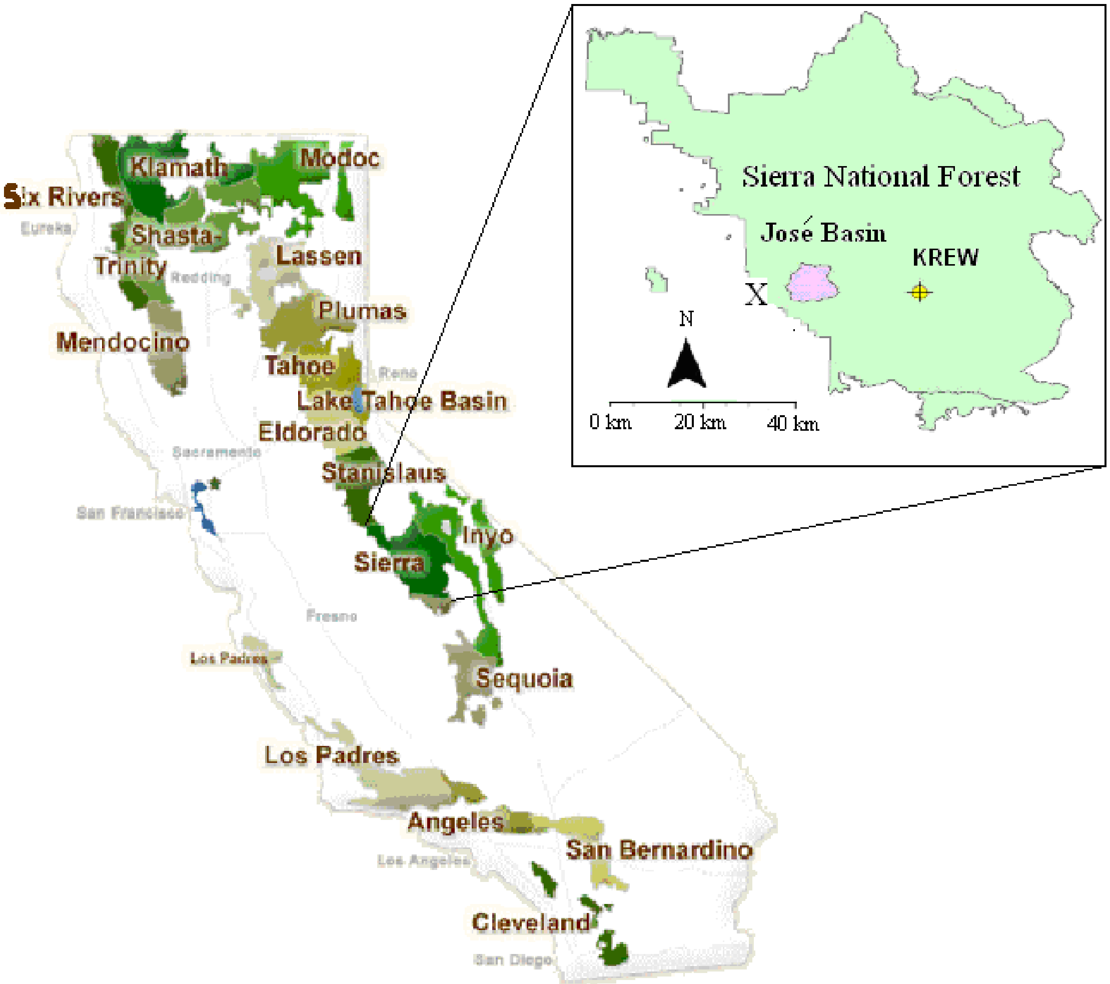

Figure 2.1. Location of the national forests in California, including the Eldorado and the Sierra National Forest (SNF). Inset of the SNF shows José Basin and the Kings River Experimental Watershed (KREW). X indicates the location of the Auberry precipitation gage (CA map from http://www.fs.fed.us/r5/forests.shtml).

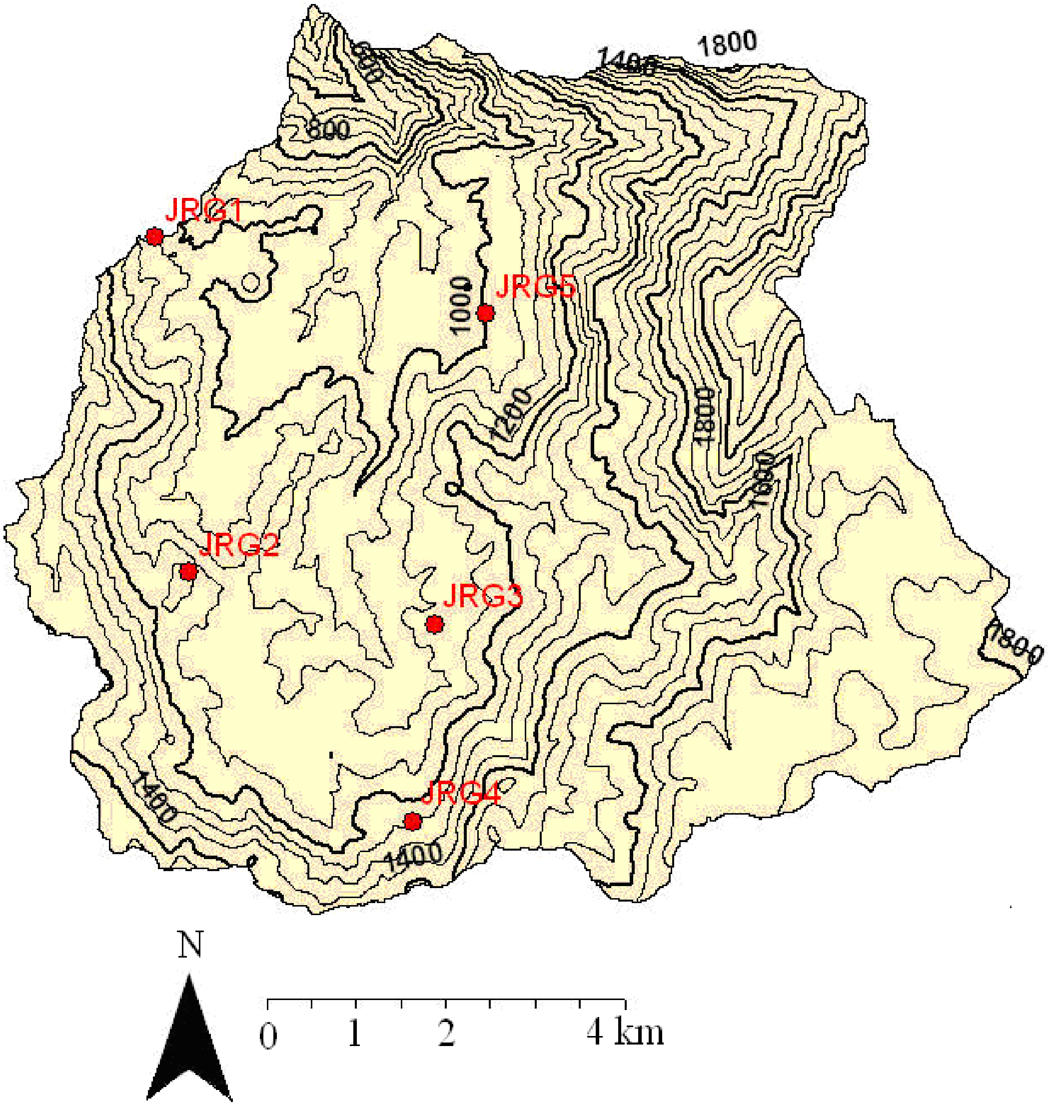

Figure 2.2. Elevation contours and the location of the five rain gages (JRG1-JRG5) in José Basin (derived from digital elevation maps in the SNF data base, accessed via A. Gallegos, 2007).

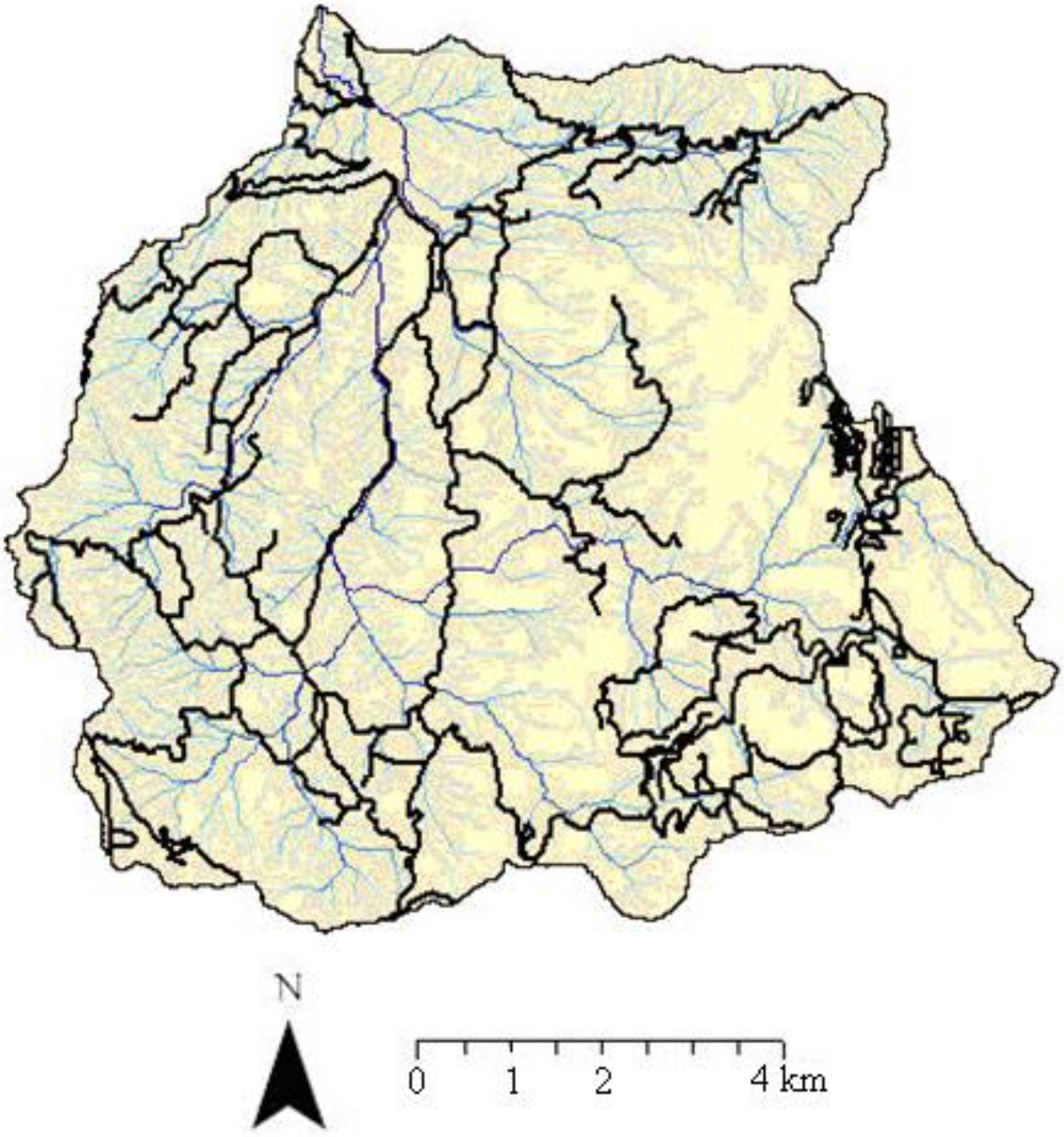

Figure 2.3. Roads (in black) and streams (in blue) in José Basin (data from the SNF data base, accessed via A. Gallegos, 2007). Colored areas in the background represent convergent areas that are likely wet or contain flow during the wet season from approximately October through May.

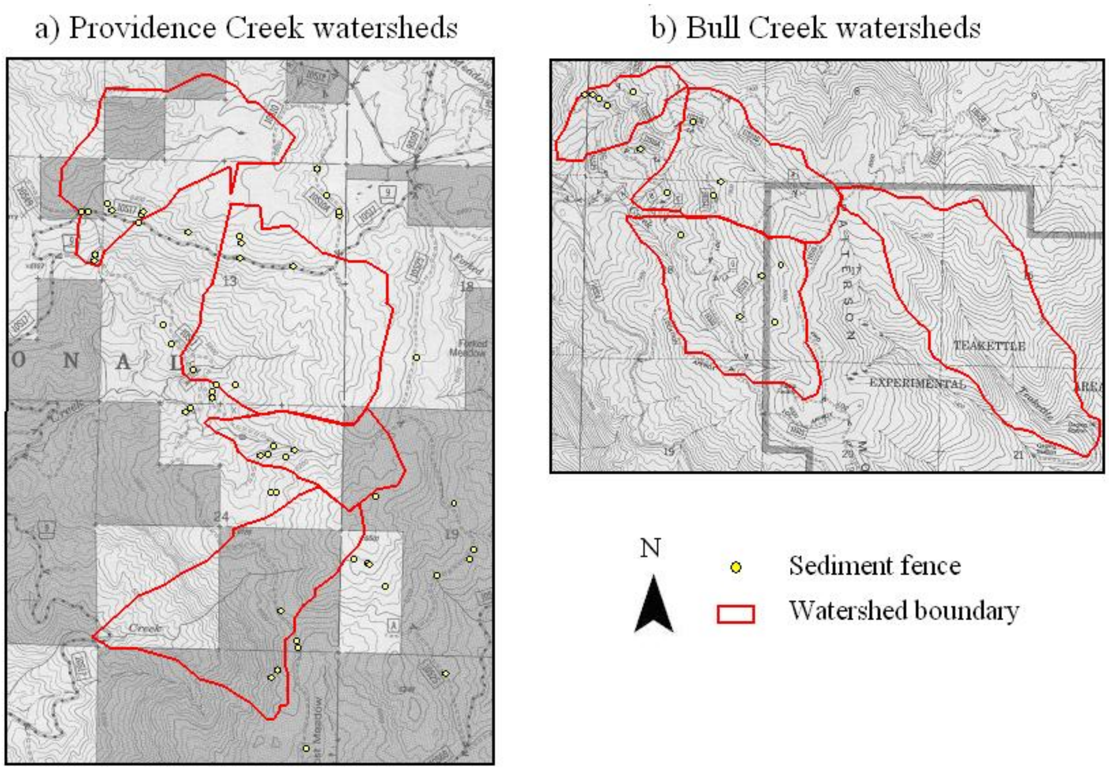

Figure 2.4. The King’s River Experimental Watershed (KREW) contains two sets of four watersheds. The lower elevation Providence Creek watersheds (a) have elevations ranging from 1485 to 2005 m, while the higher elevation Bull Creek watersheds (b) range from 2050 to 2420 m (Korte, 2005). Sediment fences on roads are indicated by yellow circles, and sediment fences on hillslopes are indicated by yellow circles with attached contributing areas in blue (figures from Korte, in preparation).

Figure 2.5. Sediment fences were installed on undisturbed, convergent swales in José Basin and the Providence Creek and Bull Creek watersheds. The fabric floor facilitates sediment removal and the accuracy of the measurement (photo by A. Korte).

Figure 2.6. Sediment fences were installed at the drainage point of native surface road segments in José Basin as well as the Providence Creek and Bull Creek watersheds. This fence was installed just below a waterbar draining a native surface road segment in José Basin in summer 2007.

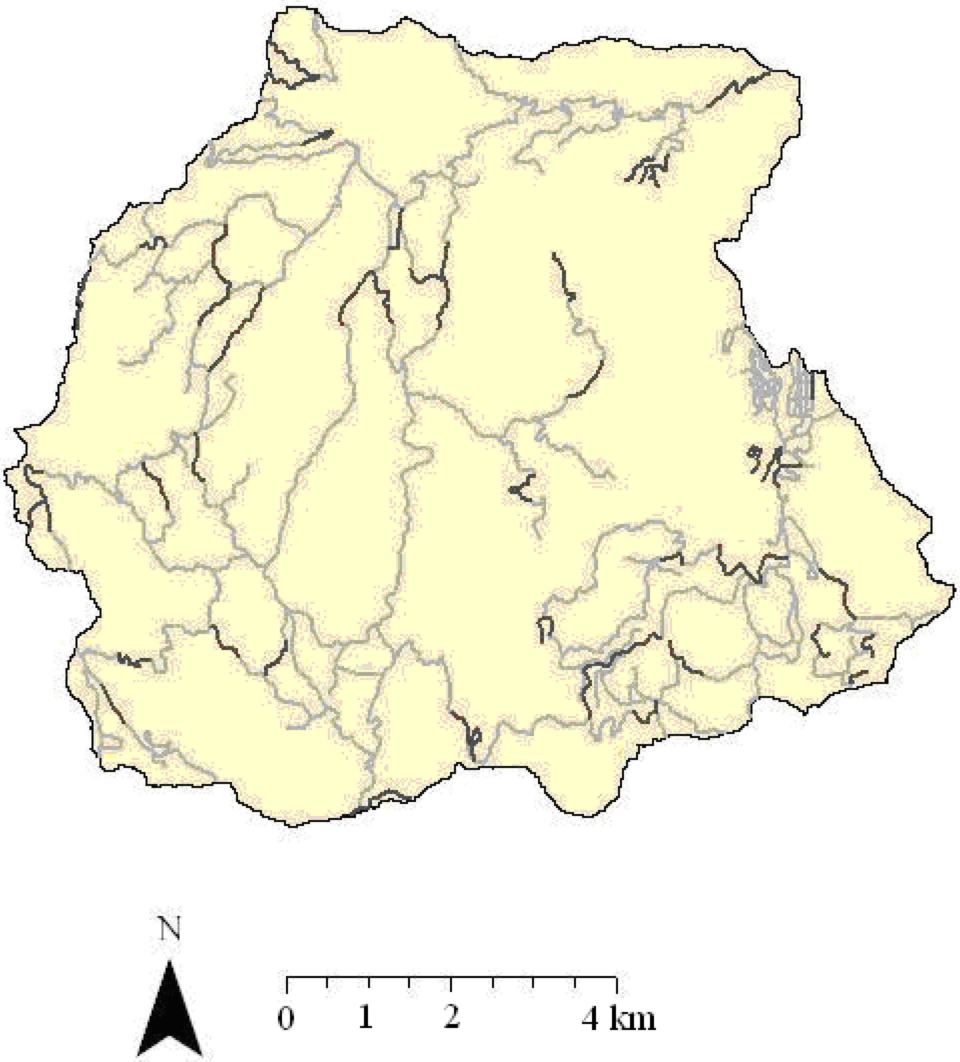

Figure 2.7. Location of the road sections (in black) in José Basin that were randomly selected to be surveyed. The remainder of the road network is shown in grey.

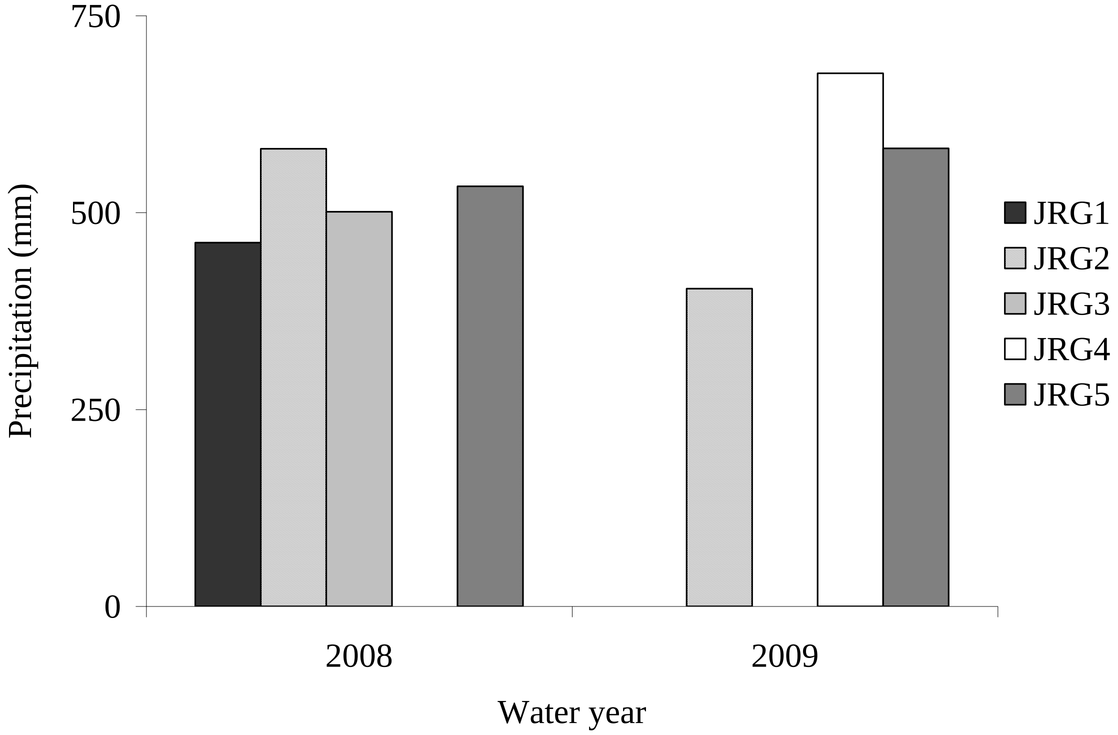

Figure 2.8. Annual precipitation for the rain gages in José Basin. Four rain gages functioned during WY2008 and three gages in WY2009.

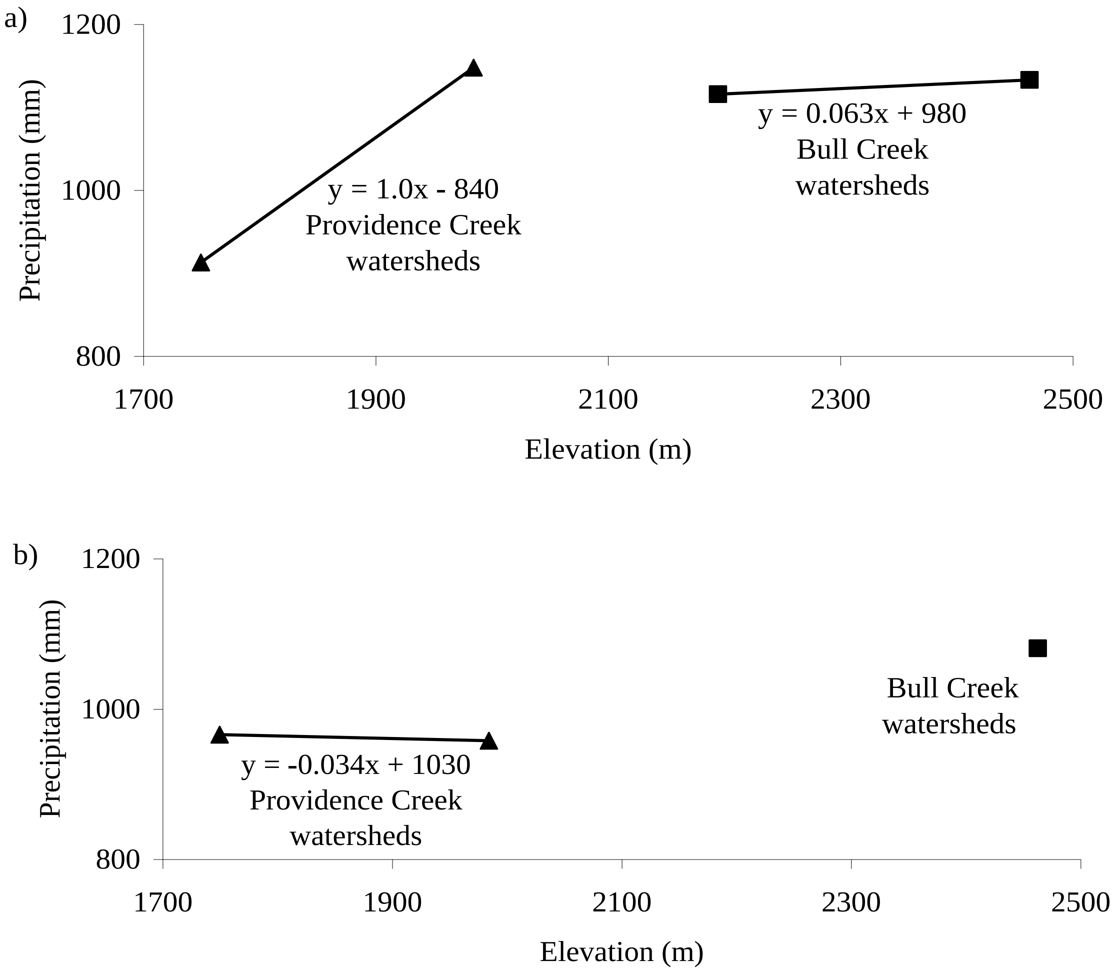

Figure 2.9. Precipitation versus elevation for the Providence Creek and Bull Creek watersheds for (a) WY2008 and (b) WY2009.

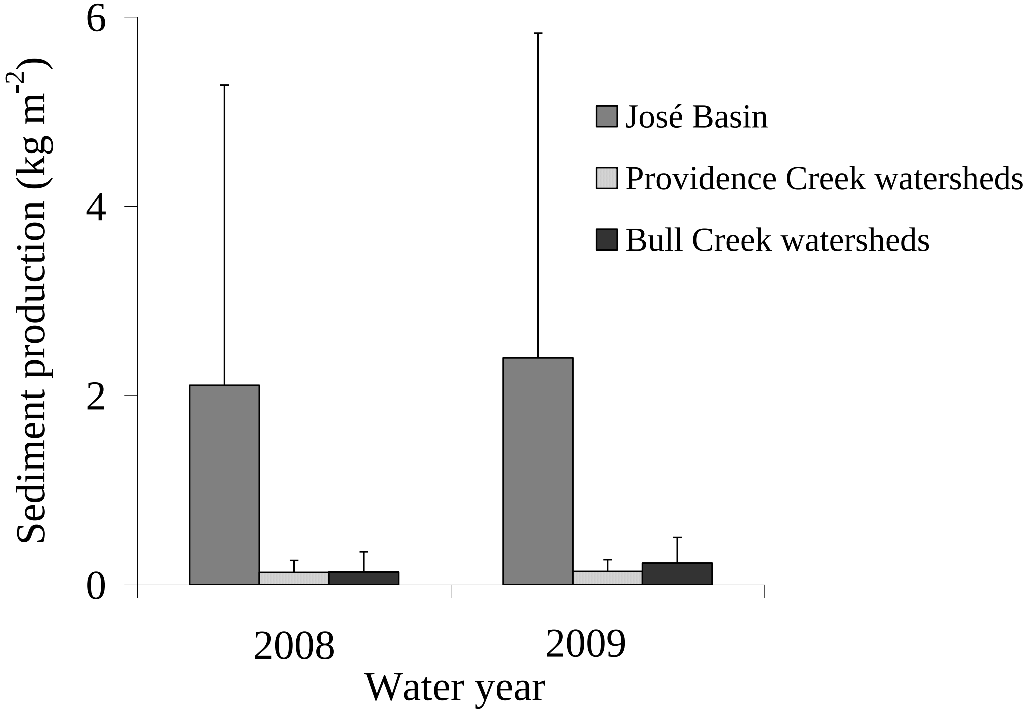

Figure 2.10. Mean sediment production rates for native surface road segments in José Basin, the Providence Creek watersheds, and the Bull Creek watersheds for WY2008 and WY2009. Error bars display one standard deviation.

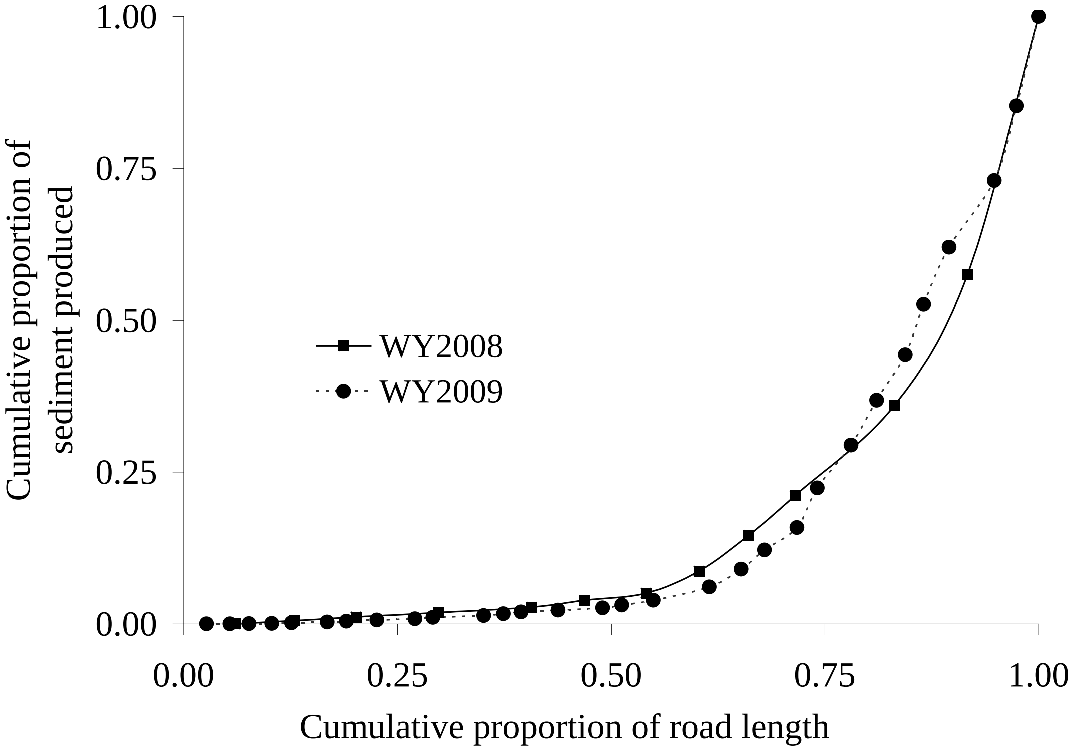

Figure 2.11. A relatively small proportion of the road length monitored produced 75% of the sediment in both WY2008 and WY2009.

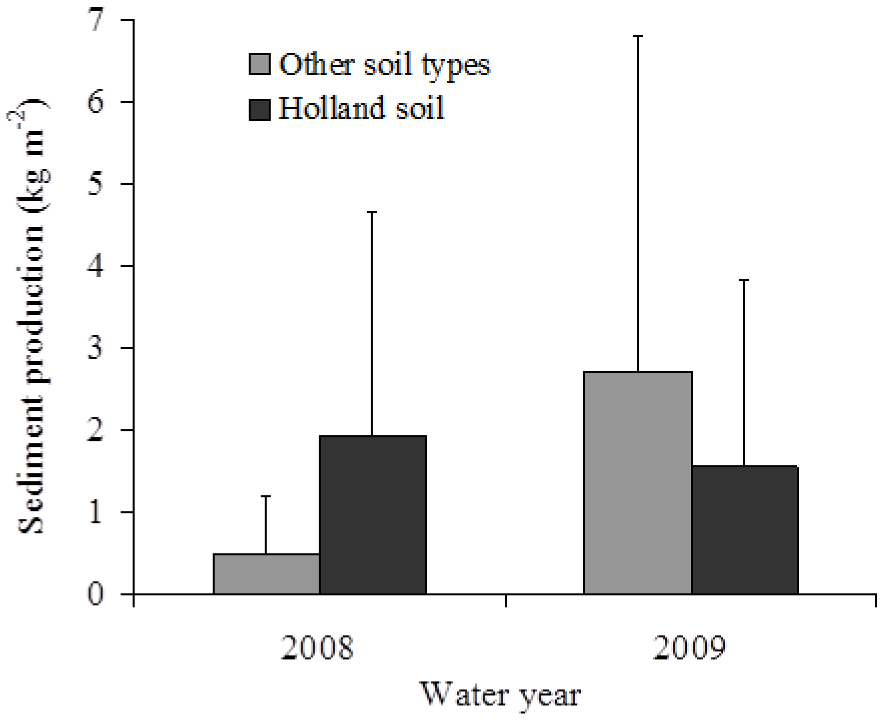

Figure 2.12. Mean sediment production rates for native surface road segments in José Basin in other soil types and in Holland soil for WY2008 and WY2009. Error bars indicate one standard deviation.

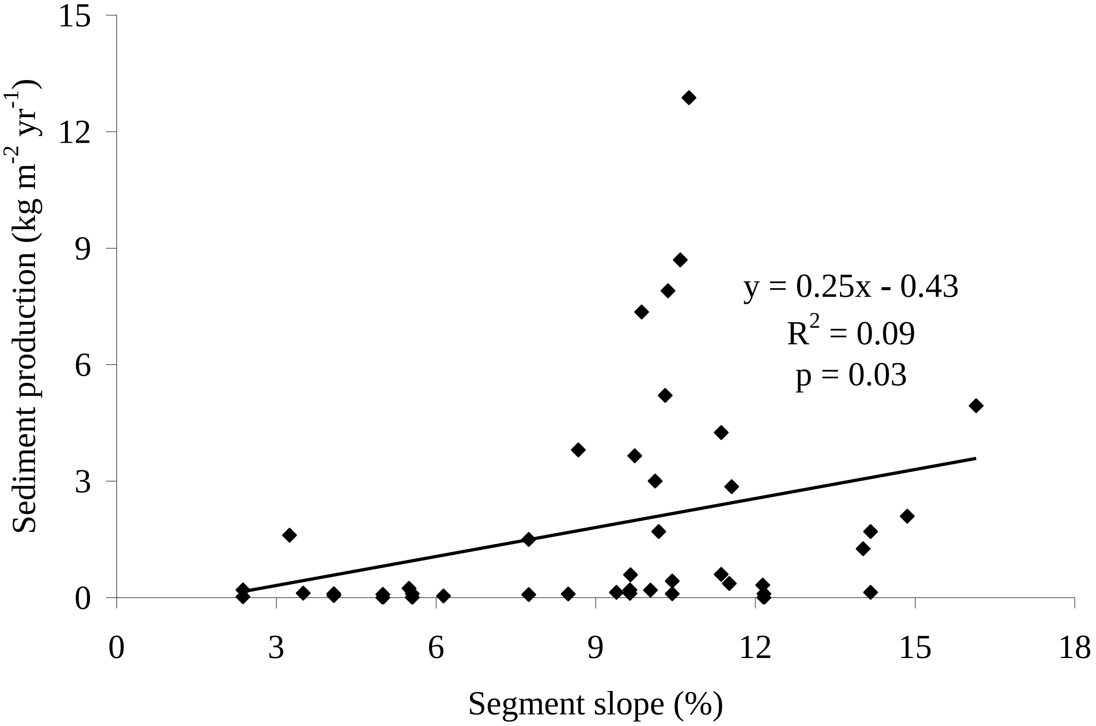

Figure 2.13. Annual sediment production and segment slope were significantly correlated for native surface road segments in José Basin (p = 0.03).

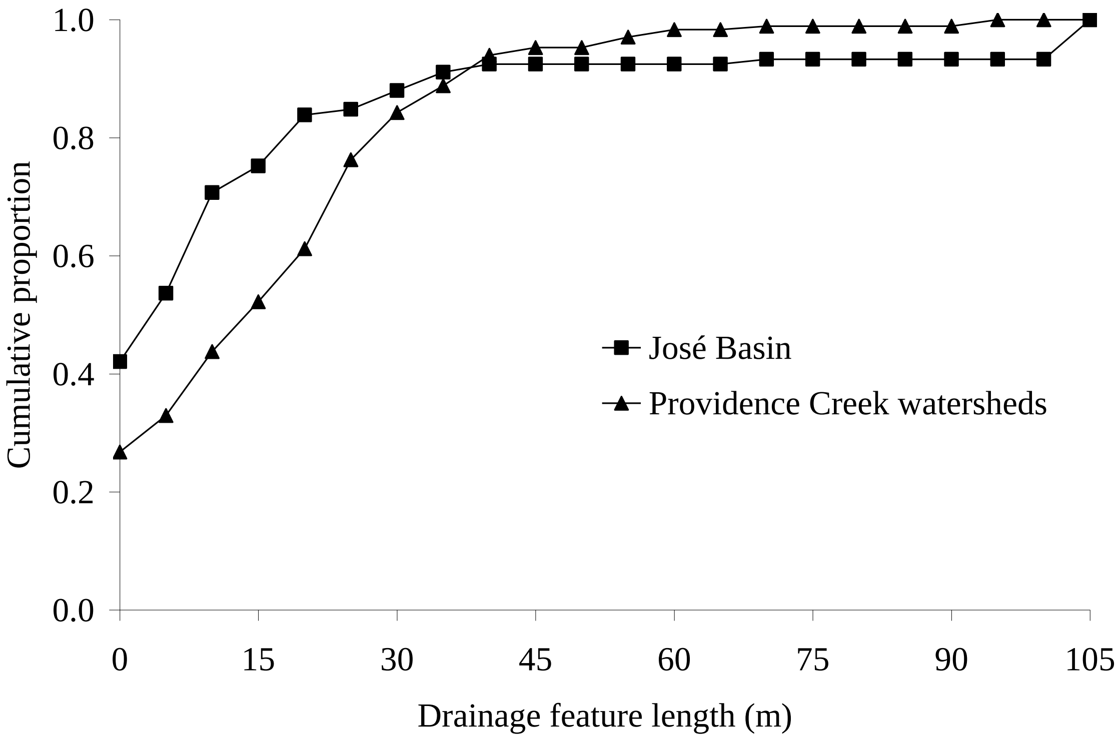

Figure 2.14. Cumulative proportion of road length by drainage feature length for native surface road segments in José Basin and the Providence Creek watersheds.

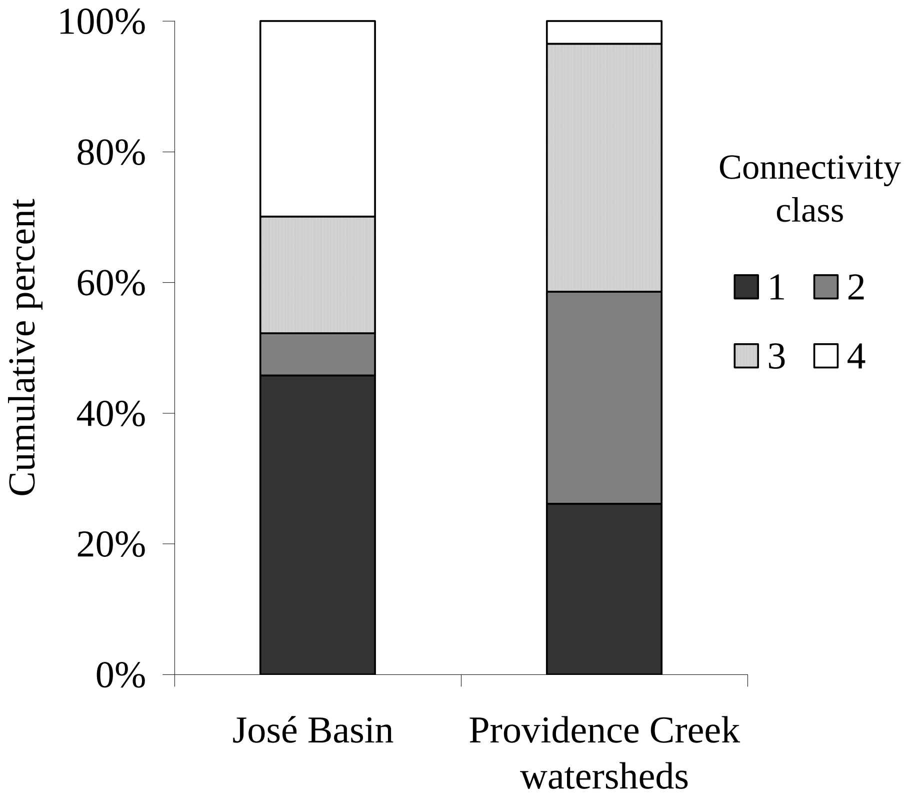

Figure 2.15. Cumulative percent of road length by hydrologic connectivity class for native surface segments in José Basin and the Providence Creek watersheds.

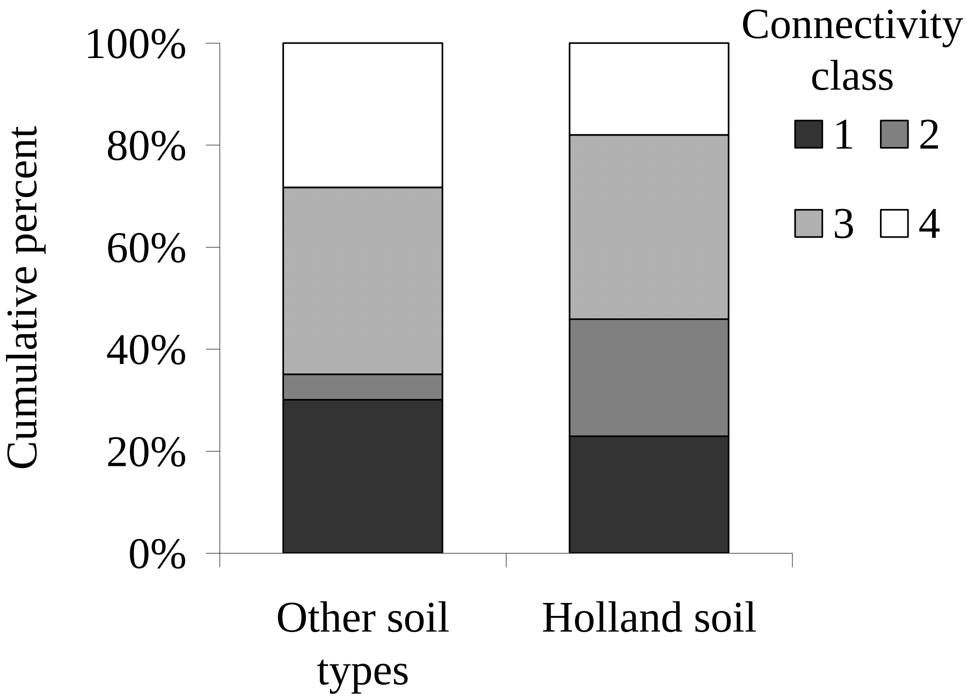

Figure 2.16. Cumulative percent of native surface road length in José Basin by hydrologic connectivity class for other soil types and Holland soil.

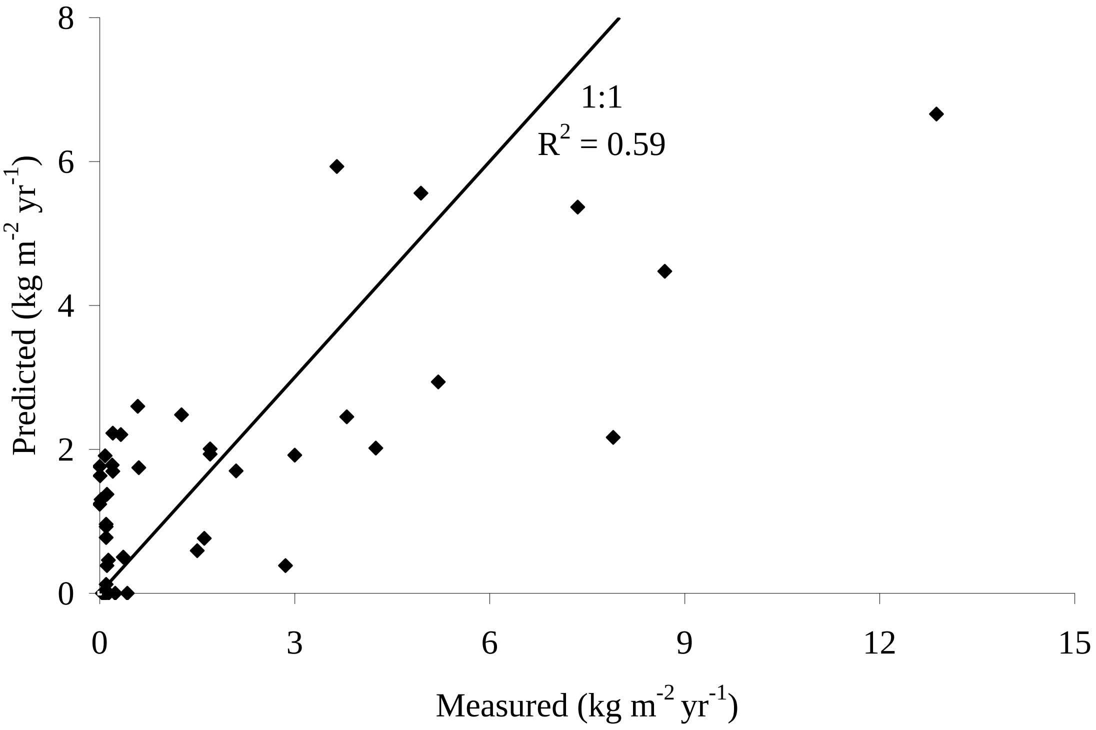

Figure 2.17. Predicted versus measured sediment production rates using the empirical multivariate model developed for native surface road segments in José Basin.

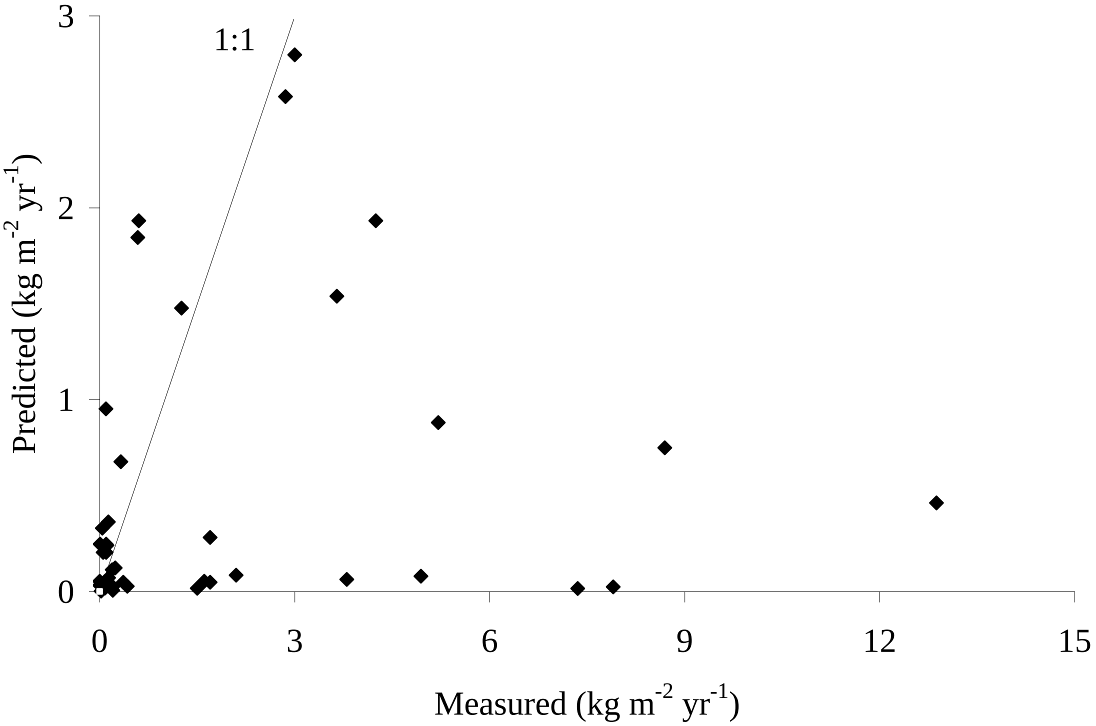

Figure 2.18. Comparison of the predicted road sediment production using WEPP:Road to the values measured in José Basin (n = 43).

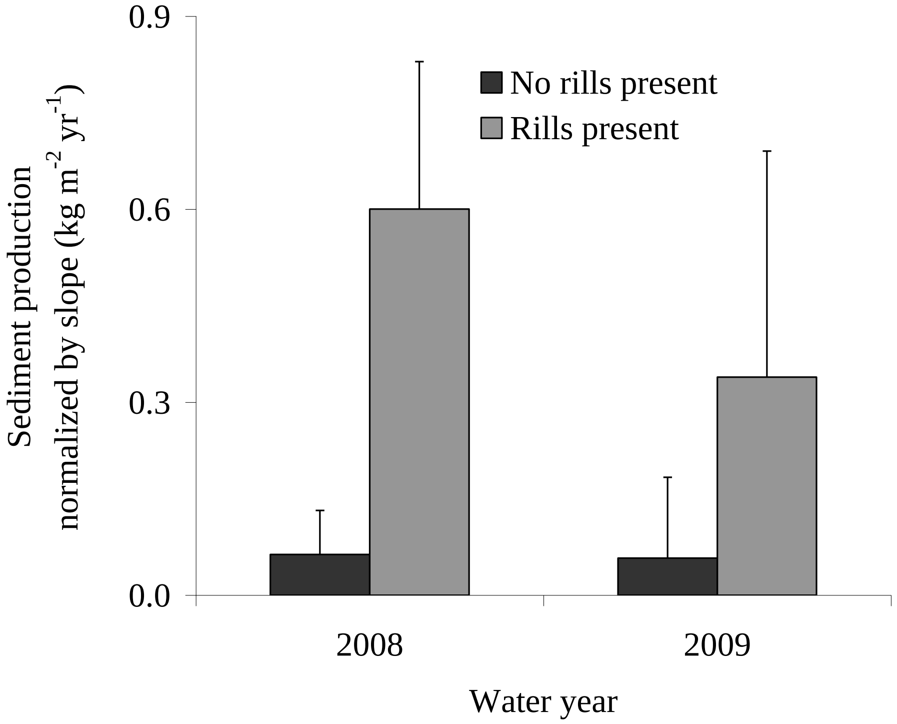

Figure 2.19. Mean sediment production rates normalized by slope for native surface segments with and without rills in José Basin for WY2008 and WY2009 ($p < 0.0001$ and $p = 0.007$, respectively). Error bars represent one standard deviation.

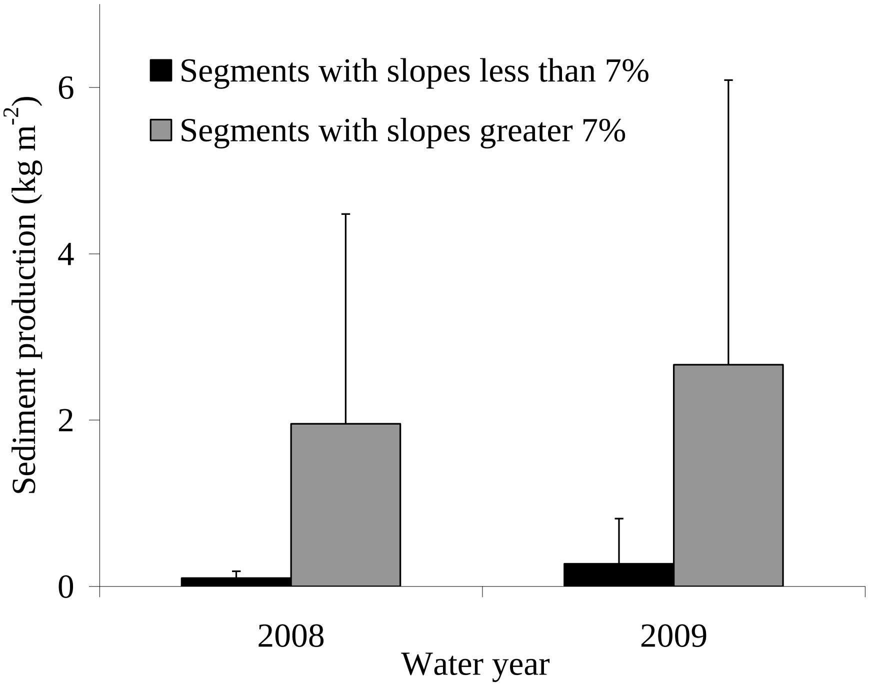

Figure 2.20. Mean sediment production rates in José Basin for native surface segments with slopes less than and greater than 7% for WY208 and WY2009 (p = 0.18 and 0.06, respectively).

3. EFFECTS OF GRAVELING AND GRADING ON SEDIMENT PRODUCTION AND DELIVERY

ABSTRACT:

Rocking, grading, and installing waterbars are common road maintenance techniques for unpaved roads, and these are intended to improve drivability and reduce both sediment production and sediment delivery to streams. A study in the Sierra National Forest, California was conducted to compare sediment production and delivery from: 1) native and gravel surface road segments in the lower elevation José Basin (800-1200 m) and the higher elevation Providence Creek watersheds (1485-1205 m); and 2) ungraded and graded native surface road segments in José Basin. Sediment fences were used to measure annual sediment production rates. Road segment characteristics such as segment length and slope were measured, and road sediment delivery was estimated by assessing each drainage feature.

For water year (WY) 2004 through WY2006, the mean sediment production rate for gravel surface segments was 0.23 kg m^2 yr^{-1} in the Providence Creek watersheds, or 14-29% of the value for native surface segments, and this difference was significant. There was no significant difference in WY2007 due to very low precipitation and road erosion rates, or in WY2008 and WY2009 due to very high sediment production rates from one gravel segment. In José Basin, gravel surface roads produced significantly more sediment than native surface segments in WY2008, and there was no significant difference in WY2009. Gravel surface segments in José Basin have only 29% gravel cover on average, which is inadequate to significantly reduce rainsplash and sheetwash erosion.

Pre- and post-treatment surveys of approximately eight kilometers of roads in José Basin indicated that grading and waterbar installation decreased the mean segment length from 65 to 41 m, but 22% of the waterbars that were installed or reconstructed failed within the first year after grading, resulting in a 15% increase in segment length. Rills developed on 31% of the segments within the first year after grading. Different comparisons in different years indicated that graded road segments produced 2.6 to 7.6 times more sediment than ungraded segments. Though grading reduced the length of road directly connected to the stream network by half, the net result was a 20-320% increase in the estimated sediment delivery to streams.

The results indicate that the frequency of grading should be reduced as much as possible to prevent an increase in sediment delivery. Waterbars need to be compacted and high with adequate cross-slope to direct water off the surface. Restricting traffic under wet conditions can reduce the occurrence of waterbar failure and the need for grading.

Allison K. Stafford
Department of Forest, Rangeland, and Watershed Stewardship
Colorado State University
Fort Collins, CO 80523
Spring 2011

3.1. Introduction

Increased sediment loading to streams, rivers, and lakes is a major concern, as this can adversely affect water quality, stream habitat, and aquatic ecosystems (Bilby et al., 1989; Ziegler and Giambelluca, 1997; Kolka and Smidt, 2004). The EPA lists sediment as the most common impairment to water quality in streams and lakes in the United States (EPA, 2010). Fine sediment also can decrease pool depth and abundance, and increase the turbidity of the stream (Beechie et al., 2005), both of which can alter the quality and quantity of habitat for salmonids and limit reproduction (Harr and Nichols, 1993; Weaver and Hagans, 1999; Beechie et al., 2005). Increased sediment loading also can affect aquatic organisms by altering stream temperatures and nutrient loads (Kolka and Smidt, 2004). The U.S.D.A. Forest Service lists sediment as one of the primary impairments to water quality in North American forests, along with pathogenic organisms, organic material, nutrients, dissolved solids, and toxics (Brown and Binkley, 1994).

Sediment loading in streams occurs when surfaces that are hydrologically connected to the stream erode. Hillslope sediment production rates in undisturbed forested watersheds are typically very low (MacDonald et al., 2004), as forests have a dense surface cover of vegetation and litter and a high porosity and infiltration rate. These characteristics largely prevent soil detachment and overland flow (Dunne and Leopold, 1978). Surface disturbances such as fire, concentrated grazing, or road construction can expose the mineral soil and reduce the infiltration rate (MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2005). This can result in a higher likelihood for the occurrence of erosive overland flow, which can detach the exposed mineral soil particles and transport them to the stream network.

Unpaved roads typically have a high percentage of exposed mineral soil that is susceptible to detachment and transport. In forested watersheds, unpaved roads are often a major source of sediment to streams (Reid and Dunne, 1984; Swift, 1988; Bilby et al., 1989; Luce and Black, 1999; Ketcheson et al. 1999; Coe, 2006). Roads can deliver a large amount of sediment to streams relative to their surface area even during low to moderate rainfall events (Ziegler and Giambelluca, 1997; Chappell et al., 1999; Ziegler et al., 2004; Cafferata et al., 2007). Road sediment production can vary greatly both inter-annually and among road segments, which are defined as sections of the road that have clearly defined contributing areas and discrete drainage points or are outsloped (Coe, 2006; Korte, in preparation).

Rocking, grading, and installing waterbars are common treatments to reduce road sediment production, reduce road sediment delivery, and maintain road drivability. Rocking reduces sediment production by covering the bare mineral soil, thereby reducing rainsplash detachment, and also reduces the velocity of overland flow, which further reduces detachment and sediment transport (Megahan et al., 1991; Poesen et al., 1994; Appelboom et al., 2002; Sheridan and Noske, 2007; Rivera et al., 2009). Grading, while maintaining drivability, typically increases the supply of finer soil particles that can be readily detached by rainsplash and sheetwash and thereby often increases sediment production (Megahan and Kidd, 1972; Megahan, 1974; Reid and Dunne, 1984; Megahan et al., 1986; Luce and Black, 1999; Ziegler et al., 2000; Ziegler et al., 2001; Appelboom et al., 2002; Ramos-Scharrón and MacDonald, 2005; Coe, 2006). If flow becomes concentrated, severe rilling may occur, which can increase sediment production and reduce road drivability. Installing waterbars reduces the contributing area of a road segment, which should decrease the amount of concentrated runoff and sediment production (Chapter 2). By altering segment length and drainage from a road, waterbar construction and maintenance can reduce road-stream connectivity and sediment delivery to the stream network.

These issues are of particular concern on National Forest lands in the Sierra Nevada, and the present study follows from two earlier projects. The first study in the Eldorado National Forest in the northern Sierra Nevada (Figure 3.1) measured sediment production rates from 15 native surface road segments that were not recently graded, 2-40 recently graded road segments, and 9-10 ungraded gravel surface road segments from water year (WY) 2000 to 2002 (Coe, 2006).

The second study was centered on the Kings River Experimental Watershed (KREW) in the Sierra National Forest (SNF) in the southern Sierra Nevada (Figure 3.1). In this area precipitation falls mainly as snow, although occasional rain or rain-on-snow events may occur. From WY2004 to WY2006, sediment production was measured from 11-13 native surface, seven gravel surface, and four mixed surface road segments as well as from seven ditches adjacent to paved roads (Korte, in preparation). Both of these studies also conducted extensive road surveys to characterize the road network and evaluate road-stream connectivity.

This study continued the measurements of road sediment production from different road surface types in the KREW watersheds, but the primary focus was shifted to the lower elevation José Basin, which is also located in the SNF. José Basin is a 78 km^2 watershed approximately 20 km west of KREW (Figure 3.1), and here the precipitation falls primarily as rain. The specific objectives of this portion of the study were to: 1) quantify the effect of road surface type on sediment production and delivery in KREW under a range of climatic conditions; 2) quantify the effect of graveling on road sediment production and delivery in José Basin; 3) predict the total sediment delivered from gravel surface roads to the stream network in José Basin; 4) quantify the effect of grading and waterbar installation on road segment characteristics, road sediment production, and road sediment delivery in José Basin; and 5) quantify the effect of rill erosion on sediment production following grading in José Basin.

3.2. Background

3.2.1. Road sediment production and delivery

Road surface sediment production is the result of several erosional and transport processes. These include: 1) rainsplash detachment, 2) sheetwash, and 3) rill erosion (Zeigler et al., 2000). Rainsplash detachment occurs when the impact of a raindrop detaches fine sediment from the road surface (Zeigler et al., 2000). The rate of rainsplash detachment is highly dependent on the rainfall erosivity, which in turn is a function of the precipitation intensity and the drop size distribution (Lal, 1988; Renard et al., 1997).

When rainfall intensity exceeds the infiltration capacity of a surface, water flows downslope as infiltration-excess or Horton overland flow (HOF) (Dunne and Leopold, 1978). Sheetwash and rill erosion occur when the shear stress applied by this overland flow exceeds the resistance of the surface (Dunne and Leopold, 1978).

The amount of sheetwash and rill erosion is directly related to the force of the flow and the surface erodibility (Luce and Black, 1999; Croke and Hairsine, 2006). The force of a given flow is related to the depth and velocity of flow (Dunne and Leopold, 1978). The depth and velocity of flow are functions of the duration and intensity of a given precipitation event relative to the infiltration rate (Dunne and Leopold, 1978).

Infiltration rates on unpaved roads tend to be very low due to compaction. Values in Idaho, Colorado, and Montana ranged from 5×10^{-5} to 8.8 mm h^{-1} with a geometric mean of 0.11 mm h^{-1} (Luce and Cundy, 1994). Given a spatially uniform precipitation rate and no contribution from the adjacent hillslope, the discharge from a road segment is a direct function of the area of that segment (Leopold et al., 1964). Given a discharge, the slope and roughness of a road segment determines the flow velocity and hence the erosive energy of the discharge (Dunne and Leopold, 1978). Therefore the detachment, shear stress, and sediment transport capacity of overland flow are direct functions of the precipitation characteristics (Dunne and Leopold, 1978), the contributing area and slope of a road segment, and the road surface characteristics (Anderson and MacDonald, 1998; MacDonald et al., 2004; Coe, 2006).

As the runoff becomes channelized into rills, the detachment and transport capacity increases because the flow is deeper and faster (Merz and Bryan, 1993; Brunton and Bryan, 2000). It follows that the amount of rilling varies with precipitation characteristics and soil properties (Brunton and Bryan, 2000). Road sediment production was found to be strongly related to rill density in Colorado ($R^2 = 0.57$, $p < 0.0001$) (Welsh, 2008), and on exposed hillslopes rill erosion can be the primary sediment source rather than sheetwash (Pietraszek, 2006). Excessive rilling on unpaved roads reduces drivability and grading may be needed to restore a smooth, drivable surface. Excessive rill erosion following grading may result in the need for repetitive grading, and previous studies have not quantified the contribution of rill erosion to sediment production after grading.

The effects of unpaved roads on runoff and erosion may not be a concern unless a road is hydrologically connected to a stream, lake, or other area of concern (Wemple et al., 1996; La Marche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001). In some areas most of the connected segments are due to road-stream crossings (Wemple et al., 1996; Croke and Mockler, 2001; Coe, 2006), but road-stream crossings are not common in either KREW or José Basin. In these areas road-stream connectivity is primarily due to HOF from the road surface forming a small channel or sediment plume that extends to the stream network (Montgomery, 1994; Wemple et al., 1996; Croke and Mockler, 2001; La Marche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001). The overall increase or decrease in sediment contributed to the stream after any type of road maintenance is therefore the combination of the impact on sediment production and the impact on sediment delivery.

3.2.2. Effects of graveling on road sediment production and delivery

The same factors that affect sediment production on native surface roads also affect sediment production on gravel surface roads, as they are subject to the same set of runoff and erosional processes (Sheridan and Noske, 2007). However, the relative magnitude of these processes will differ from native surface roads, so sediment production rates from gravel surface roads are typically lower than comparable native surface road segments. Much of this difference is due to the large reduction in both rainsplash and sheetwash erosion (Poesen et al., 1994; Megahan et al., 1991; Rivera et al., 2009).

The reduction in rainsplash erosion is because the surface gravel shields the finer, more easily detached sediment particles from raindrop impact. Graveling greatly reduces sheetwash erosion by reducing the velocity of flow over a road surface and shielding the finer particles from the shear stress of the overland flow. Graveling also can reduce the amount of runoff by providing a more porous surface (Appelboom et al., 2002) and possibly allowing more infiltration into the underlying native material by reducing compaction. The reduction in velocity also allows more time for water to infiltrate, which will reduce surface runoff. In Australia mean runoff ratios for gravel surface roads were only 0.55 as compared to 0.66 for native surface segments (Sheridan and Noske, 2007). In North Carolina, the runoff volume for older and newly graveled road segments respectively averaged 45% and 39% less than native surface road segments (Appelboom et al., 2002). This reduction in runoff will result in shorter drainage features, potentially reducing road-stream connectivity.

3.2.3. Effects of grading and waterbar installation on sediment production and delivery

The effects of grading and waterbar installation are often believed to be beneficial in terms of reducing sediment delivery to streams, but this is a complex issue. Grading disturbs the road surface and increases the supply of material for transport, which can lead to an initial increase in sediment production (Megahan and Kidd, 1972; Megahan, 1974; Reid and Dunne, 1984; Megahan et al., 1986; Luce and Black, 1999; Ziegler et al., 2000; Ziegler et al., 2001; Appelboom et al., 2002; Ramos-Scharrón and MacDonald, 2005; Coe, 2006). As the time since grading increases, the fine material on the road surface is eroded away and a coarser armor layer forms, which is more resistant to both rainsplash and sheetwash erosion (Ziegler et al., 2000; Ramos-Scharrón and MacDonald, 2005). The resulting reduction in sediment production rates following grading has been modeled by the equation:

$$E_t = E_n + kSe^{-kt} \qquad \text{(equation 3.1)}$$

where E_t is the sediment production rate (Mg km^{-2} day^{-1}), E_n is the sediment production rate that would be approached if no disturbance occurred (Mg km^{-2} day^{-1}), k is an index of the decline in erosion following grading (days^{-1}), S is the total rate of material available for erosion immediately after grading (Mg km^{-2} day^{-1}), and t is the time since disturbance in days (Megahan, 1974).

In the northern Sierra Nevada, road segments that were graded within the past two years produced approximately twice as much sediment as segments that had not been recently graded (Coe, 2006). This increase was more prevalent at elevations below 1400 m, where a greater proportion of the precipitation fell as rain rather than snow (Coe, 2006). There was no apparent decline in sediment production between the first and the second year after grading (Coe, 2006). On St. John in the U.S. Virgin Islands, recently graded road segments produced 2.5 times more sediment per unit precipitation than comparable non-graded roads (Ramos-Scharrón and MacDonald, 2005). In the Oregon Coast Range, grading of ditches and cutslopes resulted in a seven-fold increase in sediment production (Luce and Black, 1999).

Waterbars are often constructed or rebuilt when grading occurs. Waterbars direct flow off the road surface, which should reduce sediment production by reducing the length and hence the contributing area of a segment. However, waterbars can fail due to flow depths that exceed the waterbar height, sediment deposition upslope of the waterbar, or rill erosion through the waterbar. The strategic placement of waterbars can reduce road-stream connectivity by reducing the amount of runoff and sediment production from a single drainage point, directing flow off of the road where it can infiltrate, and disconnecting segments that would otherwise flow directly into a stream. There are very few data on the effects of waterbar failure on segment contributing length and sediment delivery, and this study will examine these effects in José Basin.

3.3. Methods

3.3.1. Site description

Providence Creek watersheds, KREW

The Kings River Experimental Watershed (KREW) contains four mid-elevation (1485 to 2005 m) watersheds ranging from 0.49 km^2 to 1.32 km^2 within the Providence Creek watershed (Figure 3.2). The area has a Mediterranean-type climate with dry summers and wet winters. Average annual precipitation is 1240 mm, with approximately 90% of the precipitation falling as snow (Korte and MacDonald, 2007). Vegetation is primarily Sierra mixed-conifer forest (Eagan et al., 2007). The area has a granitic lithology with coarse sandy loam and loamy sand soils of the Gerle, Cagwin, and Shaver series (USDA, 1983; Korte and MacDonald, 2007).

There are 12.6 kilometers of road in the Providence Creek watersheds, with half these being native surface. There are 1.5 km of gravel surface roads and 1.9 km of paved roads, and the latter are generally insloped with ditches. The remaining roads are classified as mixed surface roads, as they are a complex intermixing of native surface, gravel, and old pavement.

In recent years very little road maintenance work has been done in the Providence Creek watersheds. The majority of the graveling was done at least ten years ago, with only small patches of gravel or other maintenance practices being put into place on an as needed basis. No grading has been done in the Providence Creek watersheds in the past ten years.

José Basin

The primary study area was José Basin, and this is approximately 20 km west of KREW (Figure 3.1). Elevations range from 450 m to 1950 m, though most of the study sites were between 800 m and 1200 m elevation. Most precipitation at the lower elevations falls as rain, and in the upper portions of the basin there is usually a seasonal snowpack (A. Gallegos, USDA Forest Service, pers. comm., 2008). Rain-on-snow events can occur at any elevation depending on the sequence of warm and cold storms and the diurnal fluctuations in temperature.

There are 447 km of stream channels in José Basin and the drainage density is 5.7 km km^{-2} (Figure 3.3). The basin has 159 km of mapped roads for a relatively high road density of 2.0 km km^{-2} (Figure 3.3). Road drivability is crucial in José Basin, as there are scattered houses in some areas, and the basin is heavily used for grazing, logging, and recreational uses such as hunting and off highway vehicles. Approximately one third of the unpaved roads in José Basin have at least 20% gravel cover.

Road maintenance is relatively common in José Basin to maintain drivability. Box-drag grading is performed at least annually or more by residents on at least one road section, and more intensive grading is done by Southern California Edison to maintain road access to its properties and power lines. Less frequent grading projects with waterbar installation and reconstruction are done on an as-needed basis by the SNF to maintain drivability and decrease sediment delivery.

3.3.2. Precipitation

Providence Creek watersheds

KREW staff operates two climate stations in the Providence Creek watersheds—one at 1750 m and another at 1984 m. Fifteen-minute precipitation data have been collected from water year 2004 (WY2004) through WY2009. Annual precipitation was calculated for both climate stations. Regression equations relating elevation to annual precipitation were developed for each water year and used to estimate the annual precipitation for each site where road sediment production was being measured.

José Basin

Five tipping bucket rain gages were installed in José Basin, but equipment problems and vandalism meant that valid data were obtained from four rain gages in WY2008 and three gages in WY2009. Annual precipitation and erosivity were calculated using the RF program for each gage for each year (Petkovsek, 2001). No correlation was found between elevation and annual precipitation or erosivity for either water year, so data from the nearest functioning rain gage was assigned to each segment where sediment production was measured.

The precipitation data from José Basin was put in historical context by using data from the Auberry climate station, which is the closest long-term station. The Auberry station is at 640 m and about one kilometer west of José Basin (Figure 3.1). The mean annual precipitation at Auberry was calculated using the 95 year record. Annual precipitation in José Basin was compared to annual precipitation at Auberry for WY2008 and WY2009.

3.3.3. Sediment production

Sediment production from discrete road segments was measured using sediment fences (Robichaud and Brown, 2002) (Figure 3.4). Fences were constructed of a geotextile fabric attached to 1-2 m long pieces of 1.3 cm diameter rebar pounded 0.3-0.5 m into the ground. The leading edge of the fabric was attached to the ground with landscape staples to prevent underflow. The captured sediment was removed during the dry season and weighed in the field to the nearest 0.5 kg. Two representative samples of about 500 g were collected to determine percent moisture (Gardner, 1986) and percent organic matter (Ben-dor and Banin, 1989). The mean percent moisture and organic matter values were used to convert the field weights to a dry mass of mineral sediment. The annual sediment production rate (kg m^{-2} yr^{-1}) was determined by dividing the calculated dry mass of mineral sediment by the contributing area of the road surface.

In the Providence Creek watersheds, annual sediment production rates for native, gravel, and mixed surface road segments as well as ditches adjacent to paved roads were measured and calculated by A. Korte for WY2004 through WY2006 (in preparation). Sediment production continued to be monitored in the Providence Creek watersheds through WY2009, though the sample size for native surface segments decreased in WY2007 due to the removal of seven sediment fences that were located on Southern California Edison land (Table 3.1).

In José Basin, sediment production was measured in WY2008 and WY2009 from 13-30 native surface road segments that were not recently graded ("ungraded" segments), 5-11 gravel surface segments, and 3-24 native surface segments for one and two water years after grading (Table 3.2). More than half of the sediment fences in José Basin overtopped in WY2008, and sediment production values from the overtopped fences were excluded from all calculations. In WY2009 sediment production was measured from six matched pairs of road segments, where one segment was graded in summer 2008 while the other segment was left ungraded. These pairs also were included in the larger pool of ungraded and graded segments (Table 3.2).

3.3.4. Road segment characteristics

The key characteristics for each road segment with a sediment fence were measured or classified (Table 3.3) to help compare and explain sediment production and potential sediment delivery. The length of each segment was measured with a meter wheel. A cloth tape was used to measure the active width, which is the width of the road that is regularly driven on, and the total width, which was defined as the width from the bottom of the cutslope to the top of the fillslope. The area of the road segment was the segment length times the active width. A clinometer was used to measure the segment slope or each change of slope if the segment was not uniform, and the segment slope was then calculated as the length-weighted slope.

Percent surface cover was determined by classifying the surface at a minimum of 100 systematically spaced points sampled along a zigzag transect on the active road surface. Each point was classified as bare soil, gravel (rock with a secondary axis greater than one centimeter), litter, or live vegetation. Segments with less than 20% gravel cover were classified as native surface segments while segments with greater than 20% gravel cover were classified as gravel segments.

Traffic was classified by determining the branch order of the road relative to a main road and visual inspection. Classes ranged from very low, indicating that vehicles very rarely travelled on the road, to low, medium, and high. Drain types and drain features were classified following the categories in Table 3.4. The elevation and location of the drainage point of each segment was determined using a GPS unit. All road surveys in the Providence Creek watersheds were completed by A. Korte (in preparation) prior to this study.

The bulk density of 13 segments prior to grading was measured by the excavation method (Grossman and Reinsch, 2002). Three pits approximately 7 cm by 7 cm were dug on the road segment to the depth of the deepest rill. The excavated sediment was collected, dried for 24 hours at 105°C , and weighed. The volume of the pit was determined from the volume of 30 grade silicon sand used to fill each pit. The bulk density was calculated by dividing the mass of the excavated sediment by the pit volume, and then averaging the three measurements. Bulk density was re-measured immediately after grading using the same procedure and again one year after grading.

3.3.5. Rill volume and contribution to sediment erosion after grading

Field observations confirmed that grading results in a planar road surface. The length and volume of rills that developed in the first year after grading was measured by placing a straight edge across the road surface and measuring the rill depth at 3-4 evenly spaced locations across the rill. The cross-sectional area at that location was the average depth times the rill width. The cross-sectional area was measured for every major change in rill depth and/or width along the length of the rill, and the rill volume was calculated by:

$$\sum_{i=1}^{n} a_i l_i \qquad \text{(equation 3.2)}$$

where a is equal to the cross-sectional area (m^2) and l is equal to the rill length (m) represented by that cross-section. The mass of sediment from rill erosion for each graded segment was calculated by multiplying the mean bulk density after grading by the total rill volume, and this value was compared to the mass of sediment captured by the corresponding sediment fence to determine the proportion derived from rill erosion (Pietraszek, 2006).

3.3.6. Sediment delivery

The potential for runoff and sediment to be delivered to the stream network was evaluated for each monitored road segment by identifying and following any drainage feature, such as a sediment plume or a rill originating from the drainage point of a road segment (Coe, 2006). The maximum length and mean slope of each drainage feature was measured in the same manner as for the road segments (Table 3.3). The roughness of the drainage pathway was classified on a scale of one to four, with class one being very smooth and class four having a large amount of live vegetation, logs, woody debris, or rocks trapping or dispersing the surface runoff and sediment.

The presence or absence of pushouts at the drainage point of the road segment was observed (Table 3.3). Pushouts were classified as no longer intact if they were too filled with sediment for the water to drain, or if the surface drainage no longer directed flow to the pushout. The presence or absence of large rocks to armor either the drainage point or the road surface at a stream crossing also was observed. This drain armoring was classified as intact if it was still in place, but it was also noted whether the armoring was exposed or buried under deposited sediment. The locations of culverts were noted, and the percent of the cross-sectional area that was plugged with sediment or large woody debris was estimated. The presence of scour at the downstream end of each culvert was noted and measured if present.

The connectivity class of each road segment was determined according to the length of the drainage feature and whether this extended to within 10 m of a defined channel (Table 3.5). Segments with a connectivity class of one have very little potential to deliver runoff and sediment to a stream channel, while segments with a connectivity class of four have a high potential. Road connectivity was evaluated for the Providence Creek watersheds prior to this study (A. Korte, in preparation). The potential amount of road sediment contributed to the stream in the Providence Creek watersheds was estimated by multiplying the mean sediment production rate by the total length of the road of a given surface, the mean width of the road, and the percent directly connected. In José Basin, the potential amount of road sediment contributed to the stream was estimated using a multivariate model predicting sediment production and multiplying the total potential sediment production from gravel surface roads by the percent of road length directly connected to the stream.

3.3.7. Road surveys

Road surveys were conducted on 7.7 kilometers of roads in José Basin between 2007 and 2009 (Table 3.3). The sections to be surveyed were identified after using ArcGIS to break the road network into 269 sections that were 300 to 900 m in length. The sections were numbered and 20% of the sections were randomly selected (Figure 3.5). Each of the selected sections was surveyed following Tables 3.3 to 3.5 unless it was paved or inaccessible because it was a private road. The percent bare soil and gravel surface were estimated for road sections surveyed that did not have sediment fences.

Repeated road surveys also were conducted on approximately eight kilometers of roads in José Basin that were graded in the summer of 2008 to determine the effect of grading on segment characteristics. The first survey was conducted prior to grading, and this was repeated immediately after grading and again in summer 2009 to determine the changes that occurred over one water year.

3.3.8. Statistical analysis

The main dependent variable was the annual sediment production rate from road segments (kg m^{-2} yr^{-1}). Pairwise comparisons of road sediment production rates within a given water year were made between different road surface types in José Basin and in the Providence Creek watersheds. The effect of grading on road sediment production in José Basin was evaluated by pairwise comparisons for each water year. The validity of each comparison was assessed by comparing other key variables (e.g., segment slope, area, and percent bare soil) between groups. Pairwise comparisons also were made between bulk density values for each segment pre- and post-grading, and between immediately post-grading and one year after grading.

ANOVA tables were used to assess the relationships between each independent variable and the measured sediment production rates from gravel surface segments in José Basin. A multivariate linear regression model to predict sediment production from gravel surface road segments in José Basin was constructed using backward elimination procedures and a selection criteria of $\alpha = 0.10$, and the validity of the model was assessed by comparing predicted sediment production rates to observed values.

3.4. Results

3.4.1. Precipitation

Precipitation in the KREW watersheds falls largely as snow, though there is the potential for both rain and rain on snow events. Mean annual precipitation is approximately 1240 mm per year (Figure 3.6). In WY2004 annual precipitation in the Providence Creek watersheds was only 72% of normal, while annual precipitation was 141% of normal in WY2005 and 163% of normal in WY2006. WY2007 was the driest year with only 62% of the mean annual precipitation. WY2008 and WY2009 were 17% and 22% below normal, respectively.

Mean annual precipitation for the Auberry rain gage is only 611 mm (California Department of Water Resources, 2010), or 49% of the mean annual precipitation for the Providence Creek watersheds. In WY2008 the annual precipitation at Auberry was only 458 mm or 75% of the mean, and this is consistent with the below normal precipitation in the Providence Creek watersheds. Mean precipitation for the four functioning rain gages in José Basin was 519 mm (standard deviation (s.d.) = 50 mm), or approximately 60 mm more than at Auberry (Table 3.6). Annual precipitation was not significantly correlated with elevation in José Basin for WY2008 ($R^2 = 0.03$, $p = 0.84$). The mean erosivity of the four gages in WY2008 was 630 MJ ha^{-1} mm hr^{-1} (s.d. = 90 MJ ha^{-1} mm hr^{-1}). Erosivity was not correlated with elevation in WY2008 ($R^2 = 0.008$, $p = 0.91$).

In WY2009 the annual precipitation at Auberry was 526 mm, or 86% of the mean. Mean precipitation for the three functioning rain gages in José Basin was 554 mm, which was 35 mm more than at Auberry, but the values in José Basin were more variable than in WY2008 as the standard deviation was 139 mm. Again the measured precipitation in José Basin was not significantly correlated with elevation ($R^2 = 0.81$, $p = 0.29$). There was no significant difference in annual precipitation between WY2008 and WY2009 in José Basin ($p = 0.66$). The mean erosivity in WY2009 was only 390 MJ ha^{-1} mm hr^{-1} (s.d. = 210 MJ ha^{-1} mm hr^{-1}), and erosivity was again not correlated with elevation in WY2009 ($R^2 = 0.15$, $p = 0.74$). Erosivity in WY2009 was 38% of, and significantly less than, the erosivity in WY2008 ($p = 0.09$).

3.4.2. Effects of road surface type on road sediment production and delivery

3.4.2.1. Sediment production

Providence Creek watersheds

The 6-13 native surface road segments with sediment fences had a mean elevation of 1860 m (s.d. = 85 m) and a range of 1750 m to 1960 m. Mean segment length was 45 m (s.d. = 13 m), and the mean slope was 10% (s.d. = 3%) (Appendix E). The segments averaged 49% bare soil (s.d. = 22%), while the remaining cover consisted of duff (mean = 35%, s.d. = 22%), gravel (mean = 10%, s.d. = 22%), and live vegetation (mean = 7%, s.d. = 6%).

In WY2004 the mean sediment production rate of the 11 native surface road segments in the Providence Creek watersheds was 0.30 kg m^{-2} yr^{-1} (s.d. = 0.38 kg m^{-2} yr^{-1}) (Figure 3.7; Appendix E). In WY2005 two more segments were monitored, and the mean sediment production rate was nearly three times greater than the prior year ($p = 0.25$). This increase can be attributed to the 95% increase in precipitation (Figure 3.6) rather than the additional segments, as the two new segments had smaller sediment production rates than the mean value for the remaining 11 segments.

Precipitation and mean sediment production was higher in WY2006 than any of the other five years, as the mean production rate for the 13 native surface segments was 1.8 kg m^{-2} yr^{-1} (s.d. = 1.8 kg m^{-2} yr^{-1}) (Figure 3.7). In WY2007 precipitation was lower than in any other year and the mean sediment production rate for the six remaining native surface segments was only 0.039 kg m^{-2} yr^{-1} (s.d.= 0.091) or 2% of the value in WY2006 ($p = 0.0019$) (Figure 3.7). This was the lowest value for the six years of monitoring.

Sediment production rates were similar for the final two water years, averaging 0.12 and 0.14 kg m^{-2} yr^{-1}, respectively (s.d. = 0.14 and 0.12 kg m^{-2} yr^{-1}).

The seven gravel surface segments in the Providence Creek watersheds had 32% gravel cover on average (s.d. = 8%), which was more than three times the amount of gravel on the native surface segments. Consequently, the gravel surface segments averaged only 19% (s.d. = 9%) bare soil as compared to 48% for the native surface segments. The remaining road surface was covered with duff (mean = 40%, s.d. = s.d. = 14%) and vegetation (mean = 10%, s.d. = 8%). The gravel surface segments had similar segment areas and slopes as the native surface segments (Appendix E).

Mean annual sediment production for the seven gravel surface segments in the Providence Creek watersheds in WY2004 and WY2005 was respectively 13% and 17% of the mean rate for the native surface segments, and this difference was significant (p = 0.017 and 0.045) (Figure 3.7). In WY2006 the mean sediment production rate from gravel surface segments was 29% of the mean rate from native surface segments, which was a smaller but still significant difference compared to the native surface segments (p = 0.018). In WY2007 and WY2009 the mean sediment production rate from gravel surface segments was equal to the mean rate from native surface segments, while in WY2008 the mean sediment production rate from gravel surface segments was 49% of the mean rate from native surface segments (p = 0.30).

The interannual pattern for sediment production rates from gravel surface segments was generally very similar to the pattern for values from native surface segments. In WY2004 the mean sediment production rate for the gravel surface segments was 0.04 kg m^{-2} yr^{-1}, while in WY2005 and WY2006 the mean value was 3.5

and 3.7 times larger, respectively. This is similar to the 2.8- and 2.2-fold increases for the mean values from native surface segments for the same two water years. Similar to the native surface segments, the mean sediment production rate for gravel surface segments was highest in WY2006, the wettest year, and lowest in WY2007, the driest year. A different pattern was only evident in WY2008 and WY2009, when sediment production rates from native surface segments were nearly equal while there was a 2.5-fold increase in mean sediment production for the gravel surface segments.

The four mixed surface road segments in the Providence Creek watersheds averaged 23% bare soil (s.d. = 15%), 21% gravel (s.d. = 8%), 21% pavement (s.d. = 7%), and 38% duff (s.d. = 19%). Their mean length was 95 m (s.d. = 38 m), or 2.1 times the mean length of the native surface segments, while their mean slope was 10% (s.d. = 1%), which was the same value as the native surface segments (Appendix E).

Sediment production from the four mixed surface road segments tended to be binary, with PM1 and PM5 having sediment production rates typically one to three orders of magnitude higher than PM3 and PM4. Rills at least 8 m long formed on the two segments with higher sediment production rates, though a rill that was 16 m long and 0.8 m deep also formed on PM4. Mean annual sediment production rates from mixed surface segments were 43-62% that of native surface segments from WY2004 to WY2007. In WY2008 the mean annual sediment production rate for mixed surface roads was 0.31 kg m^{-2} yr^{-1} (s.d. = 0.26 kg m^{-2} yr^{-1}), or 4.3 times that of the native surface segments. Though precise measurements were not taken, a significant amount of erosion was observed at the knickpoint of the largest rill on PM1, which had a sediment production rate of 0.58 kg m^{-2} yr^{-1}, or 1.7 times any of the native surface segments in that year (Appendix E). In

WY2009 the mean sediment production rates from native, gravel, and mixed surface segments were nearly identical (Figure 3.7).

The ditches with sediment fences were on insloped, paved road segments that averaged 90 m long (s.d. = 50 m), twice as long as the native and gravel surface road segments. The mean segment slope was 7% (s.d. = 3%), which is slightly lower than the mean slope of 8-11% for the three other surface types. In each segment the ditches extended the entire length of the segment, and the mean ditch width was 1.0 m (s.d. = 0.2 m).

In each year, the mean sediment production from the ditches was at least an order of magnitude lower than the mean values for any of the other three road surface types (Figure 3.7). The six-year average was only 0.020 kg m^{-2} yr^{-1} (s.d. = 0.090 kg m^{-2} yr^{-1}), but in the wettest year (WY2006) this more than quadrupled to 0.090 kg m^{-2} yr^{-1} (s.d. = 0.22 kg m^{-2} yr^{-1}). The interannual variations were similar to the other road surface types, as the values increased from WY2004 to WY2006. The smallest value was in the driest year (WY2007), when none of the ditches produced any sediment.

José Basin

The number of native surface road segments with valid sediment production measurements ranged from 13 in WY2008 to 30 in WY2009. The mean elevation of these segments was 1056 m (s.d. = 83 m), 800 m lower than the mean elevation of the native surface segments in the Providence Creek watersheds. Mean segment area was 115 m^2 (s.d. = 44 m^2), which is less than the value of 168 m^2 for native surface segments in the Providence Creek watersheds (p = 0.37). Mean segment slope was 9% (s.d. = 4%), which is very similar to the mean value of 8% for the Providence Creek watersheds. Other than elevation, the only other major difference was that the native surface segments in José Basin averaged 70% bare soil (s.d. = 15%), as compared to 48% (s.d. = 17%) bare soil for the native surface segments in the Providence Creek watersheds ($p < 0.0001$).

In WY2008 the mean sediment production rate for the native surface segments in José Basin was 1.4 kg m^{-2} yr^{-1}, but this was highly variable as the standard deviation was 2.2 kg m^{-2} yr^{-1} (Figure 3.8; Appendix D). This is 2.5 times the mean value for the native surface segments in the Providence Creek watersheds, but the true difference would be even greater since 19 of the 32 sediment fences in José Basin overtopped.

In WY2009 the mean sediment production rate for the 30 native surface segments in José Basin was 2.0 kg m^{-2} yr^{-1} (s.d. = 3.1 kg m^{-2} yr^{-1}), or 43% higher than in WY2008 (Figure 3.8), even though the mean precipitation was only 6% greater (Table 3.6). The coefficient of variation was nearly identical at 155%. In WY2009 the mean sediment production from native surface road segments in José Basin was 14 times the mean value from the Providence Creek watersheds. This ratio is believed to be more representative than in WY2008 as no sediment fences overtopped.

The number of gravel surface segments in José Basin with valid sediment production values ranged from five in WY2008 to 11 in WY2009. The mean area of the gravel surface road segments was 114 m^2 (s.d = 44 m^2), and this was only nearly identical to the mean value for native surface segments in José Basin. However, the mean slope of the gravel surface segments was 13% (s.d. = 3%) as compared to 9% (s.d. = 3%) for the native surface segments, and this difference was significant ($p = 0.0001$). As expected, the gravel surface segments averaged 29% gravel (s.d. = 7%) and 51% bare soil (s.d. =

12%) as compared to 4% gravel (s.d. = 8%) and 70% bare soil (s.d. = 15%) for the native surface segments ($p < 0.0001$ in each case). The remaining cover was mostly duff (mean = 19%) and only 1% live vegetation. The mean elevation of the graveled segments was 70 m higher than the mean elevation of the native surface segments ($p = 0.0040$), but this difference is not believed to have a significant effect on sediment production (Chapter 2).

In WY2008 the mean sediment production for gravel surface segments in José Basin was 3.6 kg m^{-2} yr^{-1} (s.d. = 1.9 kg m^{-2} yr^{-1}), or 2.6 times the value for native surface segments ($p = 0.06$) (Figure 3.8, Appendix G). All five segments had sediment production rates greater than 1.0 kg m^{-2} yr^{-1}. JGH5 had a sediment production rate of 6.6 kg m^{-2} yr^{-1}, which was the highest sediment production rate for a gravel surface segment. JGH5 had only 23% gravel cover, as compared to 27-40% gravel cover for the other four segments with valid sediment data.

In WY2009 the mean sediment production for gravel surface segments was only 0.7 kg m^{-2} yr^{-1} (s.d. = 1.0 kg m^{-2} yr^{-1}), or 35% of the value for the native surface segments (Figure 3.8). The value of 0.7 kg m^{-2} yr^{-1} also was only 19% of the value for WY2008. Sediment production from the five segments with valid data in WY2008 produced only 2-51% as much sediment in WY2009, despite the lack of a significant difference in annual precipitation. The low sediment production from gravel segments in WY2009 can probably be attributed to their location within José Basin, as eight of the 11 gravel segments were located near JRG2, which had an annual erosivity of only 160 MJ ha^{-1} mm hr^{-1}. This was 290 MJ ha^{-1} mm hr^{-1} less than the WY2009 values for any of the other gages. Sediment production for each of these eight segments was less than 1.0 kg m^{-2} yr^{-1}, while each of the remaining three segments were located near JRG4, which had an annual erosivity of 570 MJ ha^{-1} mm hr^{-1} in WY2009, and they each produced more than 1.0 kg m^{-2} yr^{-1} and.

In WY2008 the mean sediment production rate for gravel surface segments in José Basin was 60 times the mean value for the Providence Creek watersheds, and in WY2009 there was a five-fold difference (Figure 3.9). These large differences can be largely attributed to the difference in elevation and thus climate, as the mean length of the gravel surface segments in José Basin was 20% less than the gravel segments in the Providence Creek watersheds ($p = 0.44$). The mean slope was only slightly steeper at 13% (s.d. = 3%) as compared to 11% (s.d. = 6%) for the gravel segments in the Providence Creek watersheds ($p = 0.21$). The gravel surface segments in José Basin did average 51% bare soil, which was much more than the mean value of 19% for the Providence Creek watersheds ($p = 0.0001$), but the gravel surface segments in both areas averaged 29% gravel cover.

3.4.2.2. Predicting sediment production for gravel surface segments in José Basin

Univariate analyses showed that annual sediment production from the gravel surface road segments in José Basin ($n = 16$) was significantly related to segment slope, segment area times slope (A*S), annual precipitation, annual erosivity, and percent bare soil (Table 3.7). The positive correlations between road sediment production and annual erosivity, annual precipitation, and the percent bare soil make physical sense. Annual erosivity had the strongest relationship with an R^2 of 0.45 ($p < 0.01$), and annual precipitation was also marginally significant at $p = 0.08$. The negative correlations between road sediment production and segment slope and area*slope did not make physical sense, and may be due to the location of longer, steeper fences in areas with higher annual erosivities. The multivariate model predicted annual sediment production from segment area (A in m^2), segment slope (S in m m^{-1}), percent bare (B), annual precipitation (P in mm), annual erosivity (E in MJ ha^{-1} mm hr^{-1}), and segment area times slope (AS in m^2 m m^{-1}) (Table 3.8):

$$SP = 17 - 0.11*A - 0.83*S + 5.63*B + 0.009*E + 0.006*AS \qquad \text{(equation 3.3)}$$

where SP is sediment production (kg m^{-2}) (Figure 3.10). The coefficients for most of these variables make physical sense, as sediment production is predicted to increase with increasing percent bare soil, erosivity, and segment area times slope. The negative relationship with area also was observed for native surface segments, as longer segments tended to have a flatter depositional area at the bottom. The predicted decrease in sediment production with an increase in slope does not make physical sense and is likely a statistical artifact. Therefore the multivariate model for predicting sediment production from gravel surface segments in José Basin is:

$$SP = -1.3 - 0.005*A + 0.004*E + 4.4*B - 0.0003*AS \qquad \text{(equation 3.4).}$$

This explains 57% of the variability in sediment production from gravel surface segments (Figure 3.10). The application of this model to the 2.5 km of surveyed gravel surface segments in José Basin yields a predicted sediment production rate of seven tons per year, or 2.8 tons per kilometer. On this basis the 29 km of gravel surface roads in José Basin are predicted to produce approximately 80 tons of sediment each year. In comparison, the multivariate model for predicting sediment production from native surface segments predicted that monitored native surface segments produced 10 tons per kilometer, and the 67 km of native surface roads in José Basin are predicted to produce 680 tons of sediment each year.

3.4.2.3. Sediment delivery

Providence Creek watersheds

Fifty-five percent of the 13.9 km of roads in the Providence Creek watersheds are native surface. Drainage features were present for 114 segments or 74% of the native surface road length, and the remaining 31 segments had no visible signs of sediment discharge. The mean length of the 114 drainage features was 20.4 m (s.d. = 14.6 m), but the mean was highly skewed by six drainage features over 50 m in length. The longest drainage feature was 94 m and this emanated from an 84 m long segment.

Despite the frequency of drainage features, only eight segments or 4% of the native surface road length was directly connected to a stream (Figure 3.11). Multiplying the mean sediment production rate from native surface roads by the total native surface road length, the mean road width, and the percent that is directly connected to a stream, the potential sediment delivered from native surface roads in the Providence Creek watersheds was 470 kg yr^{-1}. This is 35% of the total potential sediment delivered to streams from roads (Table 3.9).

Only 11% of the roads in the Providence Creek watersheds are gravel surface. Drainage features were present for 76% of the gravel surface road length, which is very similar to the 74% value for native surface roads. The mean length of the drainage features was 16.5 m (s.d. = 15.9), which was 19% less than the mean length from the native surface roads ($p = 0.21$). There were fewer long drainage features, as drainage features longer than 20 m were found for only 21% of the road length. The longest plume was 88 m long from a 51 m segment, but this was the only drainage feature from a gravel surface road that was longer than 30 m.

Eleven percent of the gravel surface road length was directly connected to the stream network as compared to 4% for the native surface roads (Figure 3.11). Gravel surface segments are estimated to contribute just 60 kg yr^{-1} to the stream network in the Providence Creek watersheds, which is only 4% of the total estimated sediment delivery from roads (Table 3.9).

Mixed surface roads accounted for 20% of the road network in the Providence Creek watersheds. Drainage features were present for 71% of the road length, and this was similar to native and gravel surface roads. The mean length of the 33 drainage features was 20.9 m (s.d. = 15.6 m), which again is nearly equal to the value for native surface roads. The mixed surface roads, like native surface roads, had several longer drainage features, with 29% of the road length having drainage features longer than 25 m. Three segments had drainage features between 30 m and 40 m long, and one 34 m long segment had a drainage feature that was 90 m long.

Thirty-one percent of the mixed surface roads were directly connected to the stream network, and this was eight and three times more than the native and gravel surface roads, respectively (Figure 3.11; Table 3.9). The high sediment production rate and high connectivity means that mixed surface roads are estimated to contribute nearly 800 kg yr^{-1} of sediment to streams in the Providence Creek watersheds, or 59% of the total (Table 3.9). Graveling all of the native surface roads in the Providence Creek watersheds could reduce their sediment production by 78%.

Fifteen percent of the Providence Creek road network is paved, and the paved roads are typically insloped with adjacent ditches. Only 21% of the paved road length had a sediment plume or rill, and three of the six drainage features were less than 10 m long. The longest drainage feature was nearly 43 m long, and this discharged from an 81 m long segment.

Surprisingly, 16% of the paved roads were directly connected to the stream network, which was four times the rate of native surface roads (Figure 3.11). Since the sediment production rates are lower for ditches than any of the three road surface types, the ditches are estimated to contribute only 23 kg yr^{-1} of sediment to the stream network, or 1% of the total.

José Basin

The road survey showed that 42% of the 159 km of roads in José Basin were native surface, 18% were gravel surface, and 41% were paved. Only 52 native surface segments, or 54% of the surveyed native surface road length, had a drainage feature (Figure 3.12). Drainage features from native surface road segments in José Basin were typically short, as only four segments had drainage features longer than 30 m. The mean length was 13.6 m (s.d. = 17.8 m), or 33% less than the mean length of drainage features from native surface roads in the Providence Creek watersheds. The longest drainage feature was 105 m and emanated from a 246 m long segment.

Thirty percent of the native surface road length was directly connected to the stream network, which is nearly an order of magnitude more than in the Providence Creek watersheds (Figure 3.13). The higher connectivity in José Basin is because many of the roads are located near streams; the mean drainage feature length of the connected segments was only 6.1 m (s.d. = 10.8 m).

Gravel surface roads accounted for 41% of the road length surveyed in José Basin. Eighty-four percent of the gravel surface road length had a drainage feature as compared to 54% for the native surface roads (Figure 3.12). Drainage feature lengths for the gravel surface segments were typically short, as 87% of the gravel surface road length had drainage features less than 10 m long. The longest drainage feature was only 22 m long, and this came from a 45 m long segment. The connectivity classes for gravel surface roads also had a binary distribution, as 55% of the road length had a connectivity class of one and 40% of the road length was directly connected to the stream network (Figure 3.13).

3.4.2.4. Total potential sediment delivered from gravel surface segments in José Basin

As calculated in the previous chapter using the multivariate model for predicting sediment production from native surface roads,, native surface roads are estimated to contribute 210 tons of sediment per year to the stream network in José Basin (Table 3.9). This is 87% of the total potential sediment delivered from roads to streams (Table 3.9), and more than two orders of magnitude more than native surface segments in the Providence Creek watersheds. Native surface segments in José Basin are estimated to contribute

As calculated using the multivariate model for predicting sediment production from gravel surface roads, the 29 km of gravel surface roads in José Basin are predicted to produce 80 tons of sediment per year. Since 40% of the gravel surface segments are connected, up to 32 tons yr^{-1} of sediment are delivered to the stream network from gravel surface roads. This is just 13% of the estimated sediment delivery from native surface segments. Since the gravel surface segments in José Basin have comparable sediment production rates and a 33% higher connectivity, most of the eight-fold difference in sediment delivery between gravel and native surface roads is due to the much greater amount of native surface roads (67 km vs. 29 km). The remaining 3.2-fold difference is due to differences in the derived models as well as differences in the representativeness of the monitored segments to all of the native and gravel surface segments in José Basin.

3.4.3. Effects of grading in José Basin

3.4.3.1. Effects of grading on segment characteristics

Approximately eight kilometers were graded along six different roads in José Basin in summer 2008. Prior to grading, the mean length of the 124 segments was 65 m, but the variability was very high as the standard deviation was 104 m (Figure 3.14; Appendix H). Thirteen segments were greater than 100 m long, and the longest was 1124 m. There were 109 waterbars on these road segments, but the field assessment indicated that only 53% of the waterbars were functioning properly. Waterbar failure was due to on-segment deposition on the upslope side of the waterbar, rill erosion through the waterbar, and flow depth that exceeded the height of the waterbar.

During grading 128 waterbars were either installed or reconstructed, and this decreased the mean segment length from 65 m to 41 m (Figure 3.14). Segment length became much more uniform as the overall standard deviation dropped from 104 m to 26 m. Only six segments were longer than 100 m, and the longest segment was 175 m.

The repeat survey one year after grading showed an overall increase in mean segment length of 15% to 47 m, and a 31% increase in the overall standard deviation. The increase in mean segment length was true for all six roads. The increase in mean length and standard deviation was due to the failure of 28 waterbars, or 22% of the 128 waterbars installed or reconstructed in summer 2008. Waterbar failure resulted in ten segments that were more than 100 m long and two segments longer than 200 m. Waterbar failure was again due to on-segment deposition, rill erosion, and flow depths exceeding the height of the waterbar.

3.4.3.2. Effects of grading on sediment production

The ungraded and graded native surface segments in José Basin had similar lengths and areas (Figure 3.15), but the two groups differed in slope and surface cover. The ungraded segments had an average of 9% slope (s.d. = 4%), while the graded segments averaged 14% slope, and this difference was highly significant ($p < 0.0001$) (Figure 3.15). The ungraded segments had 71% bare soil on average (s.d. = 15%), and the graded segments had 81% bare soil (s.d. = 14%). This significant difference ($p = 0.0048$) is due to the blading technique used in grading, which scrapes accumulated duff and vegetation growth off of the road surface. The ungraded and graded segments had only 4% and 5% gravel cover, respectively (s.d. = 8% and 6%).

In WY2008 the 13 ungraded native surface segments in José Basin had a mean sediment production rate of 1.4 kg $m^{-2}yr^{-1}$, but the data were highly skewed as indicated by the high standard deviation of 2.2 kg m^{-2} yr^{-1} (Figure 3.8; Appendix D). One ungraded segment (JNO6) did not produce any sediment and 11 of the 13 ungraded segments had sediment production rates less than 2 kg m^{-2} yr^{-1}, but one segment (JBT14) produced nearly 7.9 kg m^{-2} yr^{-1}.

In WY2008, valid sediment production data were obtained from only three of the nine graded segments in WY2008, as the sediment eroded from the other six segments overtopped the sediment fences. The mean sediment production rate for these three segments was 10.6 kg m^{-2} yr^{-1} (s.d. = 3.9 kg m^{-2} yr^{-1}), or 7.7 times higher than the mean value for the ungraded segments ($p < 0.0001$) (Figure 3.8; Appendix I). The range of values was from 6.1 to 13.0 kg m^{-2} yr^{-1}.

In WY2009 the mean sediment production rate from the 30 ungraded native surface segments was 2.0 kg m^{-2} yr^{-1} (s.d. = 3.1 kg m^{-2} yr^{-1}), or 43% higher than in WY2008 (Figure 3.8). One third of the segments had sediment production rates greater than 2 kg m^{-2} yr^{-1}. The sediment production rate for JNO3 was 12.9 kg m^{-2} yr^{-1}, which was the highest sediment production rate for an ungraded native surface road segment in either WY2008 or WY2009.

In WY2009 the mean sediment production for the 24 graded segments was 5.1 kg m^{-2} yr^{-1} (s.d. = 4.9 kg m^{-2} yr^{-1}), which is 2.6 times the mean value for the ungraded native surface segments ($p = 0.0007$) (Figure 3.8). Nine of the 24 graded segments had sediment production rates greater than 5 kg m^{-2} yr^{-1}. The sediment production rate for JBT19 was 20.4 kg m^{-2} yr^{-1}, which was the highest rate among the 297 segment-years of data collected in this study between WY2004 and WY2009.

Sediment production from the ungraded and graded road segments was significantly related to segment slope ($R^2 = 0.36$, $p < 0.0001$) (Figure 3.16). After normalizing sediment production by segment slope to account for the differences in slopes between the ungraded and graded road segments, the graded road segments still produced 4.2 times more sediment per unit area than the ungraded segments in WY2008 ($p = 0.01$) and 1.6 times more sediment in WY2009 ($p = 0.06$) (Figure 3.17).

With respect to the six matched pairs of graded and ungraded segments (Table 3.10), the graded segments generally produced about five times more sediment than the ungraded segments (Figure 3.18). In one case, the graded segment generated 4.1 kg m^2 yr^{-1} while the ungraded segment produced no sediment. For the other five pairs the graded segments produced three to nine times more sediment than the ungraded segments. The graded segments did have 21% more area, 1% higher slope, and 40% more bare soil (Table 3.10), but these differences only account for 42% of the observed differences using equation 3.4.

The third comparison between graded and ungraded road segments was for four segments with one year of data prior to grading (WY2008) and one year of data after grading (WY2009). Sediment production for segments JBT2 and JBT4 was three and nearly seven times greater in the year after grading, which is much more than the overall increase in sediment production of 47% for ungraded segments from WY2008 to WY2009. In contrast, sediment production for segments JBT1 and JNU1 was much lower for the year after grading than the year before grading (Figure 3.19). The largest decline was for JNU1, which was graded by Southern California Edison, while the other three segments were graded by SNF. This variability is not readily explained, and indicates the need for sufficient replication in order to detect a significant effect.

The change in sediment production after grading was evaluated over time for the three native surface road segments graded in summer 2007. Sediment production decreased sharply from the first to the second year after grading for all three segments (Figure 3.20), as the mean value dropped from 10.6 kg m^{-2} yr^{-1} (s.d. = 3.9 kg m^{-2} yr^{-1}) in the first year after grading to 5.3 kg m^{-2} yr^{-1} (s.d. = 3.9 kg m^{-2} yr^{-1}) in the second year, or a mean decline of 52%. This decline occurred despite the 47% increase in sediment production for ungraded, native surface segments from WY2008 to WY2009.

3.4.3.3. Rill erosion after grading

Rills at least five centimeters deep formed on 31% of the 172 graded road segments within one year after grading. The length of the segments with newly-formed rills ranged from 16 m to 243 m (mean = 55 m, s.d. = 45 m), and the mean length of the segments with rills was 28% longer than the segments without rills ($p = 0.03$) (Table 3.11). The segments with rills had a significantly higher mean slope of 11% (s.d. = 4%) as compared to the mean slope of 8% for segments without rills ($p = 0.0004$) (Table 3.11). The amount of bare soil was very similar for the segments with and without rills, but the segments with rills had a mean gravel cover of only 7% (s.d. = 11%), which was half of the mean value for the segments without rills ($p = 0.017$) (Table 3.11).

The mean total rill length for the 53 segments with rills was 19.2 m and the standard deviation was relatively high at 27.5 m. The mean was skewed by two segments with more than 110 m of rills. If these two segments are excluded, the mean rill length is 9.7 m. The mean rill volume for the 53 segments was 0.22 m^3 (s.d. = 0.41 m^3), while the median was 0.08 m^3. A survey of 17 segments in summer 2008 showed a mean road segment length above the rill initiation point of 9.0 m (s.d. = 7.1) and a range of 0 m to 24 m. Rills beginning at the very top of the segment were likely headcut after initiation.

The slope of the road above the rill initiation point also was highly variable, as this ranged from three to 24% (mean = 13%, s.d. = 7%). For the area above the rill, the visually estimated percent bare soil ranged from 65-100% and the percent gravel cover was from 0-35%.

Rills formed in the first wet season after grading on all three segments with valid sediment production values. Rill volume was measured on two of these segments, and the mean value was 0.15 m^3 (s.d. = 0.05 m^3). The estimated mass of rill erosion was 196 kg or 46% of the measured sediment production on segment JBT8, and 319 kg or 49% of the measured sediment production on JBT9 (Table 3.12).

In WY2009, 19 of the 24 graded segments with sediment fences developed rills. The 19 segments with rills had a mean sediment production rate of 2.1 kg m^{-2} yr^{-1} (s.d. = 2.3 kg m^{-2} yr^{-1}), which was slightly higher than the mean value for the five graded road segments without rills (mean = 1.9 kg m^{-2} yr^{-1}, s.d. = 1.4 kg m^{-2} yr^{-1}). The mean estimated mass of rill erosion from the 19 segments with rills was 98% (s.d. = 115%) of the measured sediment production (Table 3.12), but in six cases the estimated rill erosion was more than the measured sediment production. The high values may be partially due to deposition of the eroded sediment before reaching the sediment fence. Hence the median value of 47% may more accurately indicate the proportion of sediment that is due to rill erosion, and this value is very similar to the mean value in WY2008.

3.4.3.4. Effects of grading on road surface bulk density

The mean bulk density for the 13 native surface road segments in José Basin immediately before grading was 1.56 g cm^{-3} (s.d. = 0.17 g cm^{-3}). Immediately after grading the mean bulk density was 1.52 g cm^{-3} (s.d. = 0.20 g cm^{-3}), which is only marginally lower ($p = 0.66$). The pairwise comparison for segments prior to and after grading showed that the mean bulk density for four segments decreased, the values for six segments stayed approximately equal, and the values for the remaining three segments increased (Figure 3.21).

One year after grading the mean bulk density for the same 13 segments was 1.54 g cm^{-3} (s.d. = 0.19 g cm^{-3}). Again, the pairwise comparison shows considerable variation among segments as bulk density decreased on three segments, increased on five segments, and was effectively unchanged for the other five segments (Figure 3.21).

3.4.3.5. Effects of grading on sediment delivery

The survey of approximately six kilometers of road prior to grading showed that 32% of the road length was directly connected to the stream network, while 41% of the surveyed length had no visible drainage feature. The mean drainage feature length was 14 m, but this was highly variable as the standard deviation was 18 m.

Road-stream connectivity decreased by more than half one year after grading, as only 13% of the surveyed road length was directly connected to a stream (Figure 3.22). This decrease is largely due to the breaking up of longer, hydrologically connected segments into shorter segments with no drainage feature.

3.5. Discussion

3.5.1. Effects of graveling on sediment production and delivery

Graveling is typically successful at reducing road sediment production in the Providence Creek watersheds, but there was considerable variability in the magnitude of its effectiveness between segments and between years. This variability can be attributed to variations in climate, surface cover, ad hoc maintenance, and segment characteristics.

Over the six years of monitoring the mean sediment production rate for gravel surface segments was only 22% of the mean value for native surface segments. In WY2004 and WY2005 the gravel segments produced only 13-17% as much sediment as the native surface segments, but this value increased to 29% in WY2006, which was the wettest year in the study (Figure 3.7). In WY2007, which was a very dry year, there was no significant difference in sediment production between the gravel and native surface segments (Figure 3.7). However, one segment, PG3, produced 0.23 kg m^{-2} in WY2007, which was more than an order of magnitude greater than any other gravel surface segment in WY2007. The cause of this high value is unknown, as this segment did not produce significantly more sediment than the other gravel surface segments in any of the other five years of monitoring. If this datum from segment PG3 is excluded, the mean sediment production from the gravel surface segments in WY2007 was again 18% of the mean value from the native surface segments, or very similar to the values from WY2004 and WY2005.

In WY2008 and WY2009 there was no significant difference in the mean sediment production rate between the native and gravel surface road segments. The sediment production from gravel surface segments among sites varied widely, with values ranging from zero to 0.3 kg m^{-2} in WY2008 and 0.01 to 0.4 kg m^{-2} in WY2009. In both years the sediment production from one graveled segment (PG2) was two to three times higher than any of the other graveled segments. The sediment fence for this segment was constructed 10-15 meters downslope of the road, and rilling between the fence and the road probably increased the amount of sediment captured in the sediment fence. If this segment is excluded, the mean sediment production from gravel surface segments in WY2008 was 18% of the mean value for native surface segments, which again is nearly identical to values in WY2004 and WY2005, and this difference was nearly significant ($p = 0.12$).

In WY2009 there was some ad hoc road maintenance on two gravel surface segments, PG1 and the afore-mentioned PG2. This included digging trenches for drainage and filling deep ruts with logs, and the sediment production from these two segments was respectively 2.6 and 5.3 times the mean value of 0.08 kg m^{-2} (s.d. = 0.07 kg m^{-2}) from the other five gravel segments. The increased sediment production for these two segments indicates that even small disturbances to the road surface can increase road sediment production. A third gravel segment, PG7, had a sediment production rate that was an order of magnitude higher than the maximum value for the other four untreated gravel surface segments (0.19 kg m^{-2} versus 0.05 kg m^{-2}). As with segment PG3 in WY2007, segment PG7 did not produce more sediment in the other five water years than the mean value from the other gravel segments. The increase in sediment production from this segment may be due to concentrated flow in the tire treads observed on this segment, or possibly cutslope erosion. The outliers in WY2007 and WY2009 serve as reminders that there is a great deal of uncertainty in predicting road sediment production, and the inclusion or omission of one or two sites can greatly alter the results.

Gravel should reduce road sediment production by protecting the underlying road surface from rainsplash and reducing shear stress by slowing overland flow velocities. The five-fold reduction in sediment production on the gravel segments in the Providence Creek watersheds was surprising as the percent gravel cover averaged only 29% and was generally only one rock deep. However, the runoff rates in the Providence Creek watersheds are generally low as the area is snow dominated, and a thin gravel layer may be relatively effective in reducing road surface runoff. As runoff rates increase, the effectiveness of this thin layer of gravel may be expected to decline, as the runoff is able to erode through, or detach and transport, the thin gravel layer.

Sediment production from gravel surface roads was much higher in the rain dominated José Basin than in the Providence Creek watersheds. Mean annual sediment production for gravel segments in José Basin were 60 and 5 times higher in WY2008 and WY2009, respectively. This difference is consistent with the 12-13 fold difference in mean sediment production between the native surface segments in José Basin and the native surface segments in the Providence Creek watersheds (Chapter 2).

Unlike the Providence Creek watersheds, graveling was not successful in reducing road sediment production in José Basin, even though the mean gravel cover was 29% in each study area. The two-year mean sediment production rate for the gravel segments in José Basin was nearly equal to the mean value for the native surface segments. The muted effect of graveling in José Basin can be attributed to higher annual erosivities and the average of 51% bare soil on the road surface as compared to only 18%

bare soil for the gravel segments in the Providence Creek watersheds. The lower percent bare soil for the gravel segments in the Providence Creek watersheds can be attributed to the denser forest cover at the higher elevations and the very low traffic levels, resulting in 40% litter cover. Like gravel, litter can protect the surface from rainsplash detachment and can slow the flow velocity, reducing sheetwash and rill erosion.

To be effective the gravel must be sized so that it is not easily detached by rainsplash or overland flow, and have interlocking faces rather than rounded. It also should cover the entire travelway and any inside ditch. The highest shear stress can be approximated from the rainfall intensity, contributing area, and slope, as road surface infiltration is negligible (Luce and Black, 1999). The ineffectiveness of graveling in José Basin indicates the need for more than 30% gravel cover and a gravel cover that is more resistant to the predicted shear stress based on the design rainfall intensity. With climate change the amount and intensity of rainfall in the Providence Creek watersheds may increase, and the existing gravel cover can be expected to be less effective in reducing road sediment production.

3.5.2. Effects of grading and waterbar installation in José Basin on sediment production and delivery

Grading is a routine maintenance technique for increasing drivability, but the results show that this greatly increases sediment production and can lead to an increase in the amount of sediment delivered to the stream network. In José Basin graded roads produced eight and three times more sediment per unit area than the ungraded road segments in WY2008 and WY2009, respectively. Among the matched pairs grading increased sediment production by three to nine times. A smaller increase was measured in the northern Sierra Nevada, where recently-graded road segments produced approximately two times more sediment per unit erosivity (p = 0.02) (Coe, 2006), and in the U.S. Virgin Islands, where graded segments produced 2.5 times more sediment per unit precipitation than comparable ungraded road segments (Ramos-Scharrón and MacDonald, 2005).

As with graveling, the effects of grading appear to vary with climate as this affects the amount and type of precipitation. In the Eldorado National Forest, graded segments produced eight times more sediment than ungraded segments at elevations below 1400 m (p = 0.0008), while at elevations above 1400 m there was no significant difference in sediment production between graded and ungraded roads (Coe, 2006). The large difference found at the more rain dominated lower elevations is directly comparable to the large differences observed in José Basin, which also is below 1400 m. Since no grading was done in the KREW watersheds, it is not possible to determine how the grading effect would differ with elevation and climate, but the six-year record of road sediment production in the KREW watersheds would provide an excellent opportunity to quantify the effects of grading.

The results indicate that whenever possible, the frequency of grading should be reduced to decrease the frequency of the increase in sediment production. Furthermore, the effect of grading is of particular concern in wetter, rain dominated areas because the potential increase in sediment production is likely to be higher than in higher elevation, snowmelt dominated areas.

While grading usually increases sediment production, it can decrease sediment delivery by the associated installation and repair of waterbars. Waterbars can both reduce sediment production by breaking up longer segments, and reduce sediment delivery by directing road discharge onto hillslopes and away from the streams. In José Basin, 32% of the road length was connected to the stream prior to grading, while after grading only 13% of the road length was connected. This 2.5-fold decrease in delivery did not fully compensate for the three to eight-fold increase in sediment production, suggesting that grading would result in a potential 20-320% increase in sediment delivery.

Grading may have been more successful in reducing road sediment delivery in José Basin if less than 22% of the newly installed and repaired waterbars had not failed the first year after grading. The failure of the waterbars was due to wheel ruts or rill erosion through the waterbars, sediment deposition upslope of the waterbar, and flow depths that exceeded the height of the waterbar. The management implications are that waterbars should: 1) be as high and as densely compacted as possible while continuing to allow traffic in order to maximize the likelihood that they will be effective over time; and 2) they must have a sufficient cross-slope gradient to carry the sediment off the road instead of allowing it to accumulate on the road upslope of the waterbar. Restricting driving in wet conditions will also reduce waterbar failure, as this is will greatly reduce the chance of wheel ruts cutting through the waterbar.

The larger increases in sediment production relative to the decrease in sediment delivery suggest that grading should be minimized in José Basin. A reduction in the frequency of grading to reduce sediment production rates also was recommended for roads on St. John (Ramos-Scharrón and MacDonald, 2005), state forest roads in Oregon

(Mills et al., 2007), and roads in western Montana (Sugden and Woods, 2007). The need for grading also can be reduced by restricting road use and construction during wet periods, as this reduces rut formation and helps maintain the drivability of the road (Barrett and Conroy, 2002; Sugden and Woods, 2007).

3.5.3. Monitoring and management

The relative variability in sediment production between years and between sites can be used to help determine the most efficient strategy for measuring road sediment production—is it better to monitor more sites for fewer years, or fewer sites for more years? The mean annual sediment production from gravel surface segments for the six years of monitoring in the Providence Creek watersheds ranged from 0.04 kg m^{-2} to 0.15 kg m^{-2}, and the coefficient of variation for the mean annual sediment production was 1.2. These annual mean values were very similar to the annual mean values of 0.01 kg m^{-2} to 0.21 kg m^{-2} measured for gravel road segments in the Idaho batholith (Burroughs and King, 1989).

The coefficient of variation between sites within years varied from 0.8 to 2.2 and averaged 1.4 (s.d. = 0.5). Sediment production from native surface segments in the Providence Creek watersheds was skewed, as the overall mean was 0.72 kg m^{-2} yr^{-1}, while the median was only 0.21 kg m^{-2} yr^{-1}. In the northern Sierra Nevada, mean erosion rates were also skewed by a select few gravel surface segments, so that the median value for the 30 segment-years was 0.0009 kg m^{-2} yr^{-1} while the mean value was over an order of magnitude higher at 0.12 kg m^{-2} yr^{-1} (Coe, 2006). The slightly higher coefficient of variation between sites than between years in the Providence Creek watersheds suggests that the most efficient strategy for measuring road sediment production may be to have more sites with fewer years of monitoring, although multiple years are needed to capture at least some of the interannual variability and more extreme values.

The skew and high inter-site variability also indicates that it is often just a few segments that contribute the highest sediment yields to the stream, and so practices to reduce road sediment delivery first need to pinpoint segments with high sediment production and delivery potential. As previously discussed, the higher-producing segments are typically larger, steeper segments with extensive rilling. These types of segments that feed into stream crossings or are in close proximity to streams should be the highest priority for treatment. Segments with cutslope erosion and segments with tire treads that can concentrate overland flow also should be targeted. Sediment reduction strategies should focus on rocking and/or outsloping these segments, and reducing the accumulation and delivery of overland flow by outsloping or installing waterbars.

3.6. Conclusions

Sediment production and delivery from forest roads was monitored for 249 road segment-years in the southern Sierra Nevada of California. From WY2004 through WY2009, sediment production rates were monitored on native, gravel, and mixed surface roads, as well as from ditches adjacent to paved roads in the Providence Creek watersheds (1485 m to 2005 m) of the Kings River Experimental Watershed. For two water years, sediment production rates also were monitored from native surface, gravel surface, and recently-graded road segments in José Basin, which is a lower elevation, rain dominated watershed. Road characteristics were surveyed in the two areas, and potential delivery was determined by surveying drainage features leaving the road surface and determining road-stream connectivity.

In the Providence Creek watersheds, graveling was typically successful at reducing road sediment production, but this difference was sometimes muted by individual segments with high values. Graveling all of the native surface roads in the Providence Creek watersheds could reduce their sediment production by 78%. In contrast, the gravel surface segments in José Basin did not produce significantly less sediment than the native surface segments. The thin gravel layer found in the study areas is less or ineffective at reducing road sediment production in wet years and areas with higher annual erosivity. To be effective, the gravel segments in José Basin will need more than 30% gravel cover and gravel that is either deeper or larger.

The graded road segments in José Basin produced three to eight times more sediment than ungraded segments. Rill erosion is estimated to account for approximately half of the sediment produced in the first year after grading. Grading initially decreased the mean segment length by 37%, but mean segment length increased 15% in the first year after grading due to the failure of 22% of the constructed and reinstalled waterbars. The large increase in sediment production coupled with the smaller decrease in connectivity resulted in an estimated 20-320% increase in sediment delivery in the year after grading.

The frequency of grading should be reduced as much as possible in José Basin to decrease the occurrence of a sediment pulse to the stream network. Waterbars of adequate height and cross-slope must be constructed or repaired during grading to reduce delivery. Perhaps the most beneficial best management practice to reduce sediment production from roads is to restrict traffic under wet conditions, as this will reduce waterbar failure and the need for grading.

3.7. Literature cited

Anderson, D.M., and L.H. MacDonald. 1998. Modeling road surface sediment production using a vector geographic information system. *Earth Surface Processes and Landforms* **23**: 95-107.

Appelboom, T.W., G.M. Chescheir, R.W. Skaggs, and D.L. Hesterberg. 2002. Management practices for sediment reduction from forest roads in the coastal plains. *American Society of Agricultural Engineers* **45(2)**: 337-344.

Barret, J.C., and W.J. Conroy. 2002. Improved practices for controlling both point and nonpoint sources of sediment erosion from industrial forest roads. In: *Total Maximum Daily Load (TMDL) Environmental Regulations*: *Proceedings of the March 11-13, 2002 Conference*, Fort Worth, Texas, USA. Pp. 301-306.

Beechie, T.J., C.N. Veldhuisen, E.M. Beamer, D.E. Schuett-Hames, R.H. Conrad, and P. DeVries. 2005. Monitoring treatments to reduce sediment and hydrologic effects from roads. In: *Monitoring Stream and Watershed Restoration*, Roni, R. (ed.). American Fisheries Society, Bethesda, MD, USA. Pp. 35-65.

Ben-dor, E., and A. Banin. 1989. Determination of organic matter content in arid zone soils using a simple loss-on-ignition method. *Communications in Soil Science and Plant Analysis* **20(15-16):** 1675-1695.

Bilby, R.E., K. Sullivan, and S.H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds of southwestern Washington. *Forest Science* **35**: 453-468.

Bowling, L.C., and D.P. Lettenmaier. 2001. The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. In: *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas.* Wigmosta, M.S., and S. Burges (eds.). Water Science and Application 2. American Geophysical Union, Washington, DC, USA. Pp. 145-164.

Brown, T.C., and D. Binkley. 1994. Effect of management on water quality in North American forests. USDA Forest Service GTR-RM-248, Fort Collins, CO, USA. 27 pp.

Brunton, D.A., and R.B. Bryan. 2000. Rill network development and sediment budgets. *Earth Surface Processes and Landforms* **25**: 783-800.

Burroughs, E.R., and J.G. King. 1989. Reduction of soil erosion on forest roads. USDA Forest Service GTR-INT-261, Ogden, UT, USA. 21 pp.

Cafferata, P.H., D.B.R. Coe, and R.R. Harris. 2007. Water resource issues and solutions for forest roads in California. In: *Integrated Watershed Management: Partnerships in Science, Technology, and Planning*: *Proceedings of the American Institute of Hydrology Annual Meeting and International Conference,* Reno, NV, USA. 18 pp.

California Department of Water Resources. 2010. California Data Exchange Center <http://cdec.water.ca.gov>. Accessed January 2010.

Chappell, N.A., P. McKenna, K. Bidin, I. Douglas, and R.P.D. Walsh. 1999. Parsimonious modeling of water and suspended sediment flux from nested catchments affected by selective tropical forestry. *Philosophical Transactions of the Royal Society: Biological Sciences.* **354**: 1831-1846.

Coe, D. 2006. Sediment production and delivery from forest roads in the Sierra Nevada, California. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 107 pp.

Croke, J.C., and P.B. Hairsine. 2006. Sediment delivery in managed forests: A review. *Environmental Review* **14**: 59-87.

Croke, J. and S. Mockler. 2001. Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms* **26**: 205-217.

Dunne, T., and L. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman, New York, NY, USA.

EPA, 2010. What is sediment pollution? United States Environmental Protection Agency. <www.epa.gov/owow_keep/NPS/toolbox/other/KSMO_Sediment.pdf>.

Gardner, W.H. 1986. Water content. In: *Methods of Soil Analysis Part I: Physical and Mineralogical Methods.* Klute A. (ed.). Agronomy Series No. 9, pt. 1. American Society of Agronomy, Madison, WI, USA. Pp. 493-544.

Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. In: *Methods of Soil Analysis Part 4: Physical Methods.* Soil Science Society of America, Inc., Madison, WI, USA. Pp. 201-228.

Harr, R.D., and R.A. Nichols. 1993. Stabilizing forest roads to help restore fish habitats: A Northwest Washington example. *Fisheries* **18(4)**:18-22.

Ketcheson, G.L., W.F. Megahan, and J.G. King. 1999. “R1-R4” and “BOISED” sediment prediction model tests using forest roads in granitics. *Journal of American Water Resources Association* **35(1)**: 83-98.

Kolka, R.K., and M.F. Smidt. 2004. Effects of forest road amelioration techniques on soil bulk density, surface runoff, sediment transport, soil moisture, and seedling growth. *Forest Ecology and Management* **202**: 313-323.

Korte, A. In preparation. Effects of surface type on sediment production and delivery from forest roads in the Sierra Nevada, California. M.S. thesis, Colorado State University, Fort Collins, CO, USA.

Korte, A. and L.H. MacDonald. 2007. Measuring and predicting road sediment production and watershed-scale sediment delivery. Hydrology Days presentation, Colorado State University, Fort Collins, CO, USA.

LaMarche, J.L., and D.P. Lettenmaier. 2001. Effects of flood flows on forest roads. *Earth Surface Processes and Landforms* **26(2)**: 115-134.

Lal, R. 1988. Erodibility and erosivity. In: *Soil Erosion Research Methods*. Lal, R. (ed.). Soil and Water Conservation Society, Ankeny, IA, USA. Pp.141-160.

Leopold, L.B., M.G. Wolman, and T.P. Miller. 1964. *Fluvial Processes in Geomorphology*. Freeman, San Francisco, CA, USA. 522 pp.

Luce, C.H., and T.A. Black. 1999. Sediment production from forest roads in western Oregon. *Water Resources Research* **35(8)**: 2561-2570.

Luce, C.H., and T.W. Cundy. 1994. Parameter identification for a runoff model for forest roads. *Water Resources Research* **30(4)**: 1057-1069.

MacDonald, L.H., D. Coe, and S. Litschert. 2004. Assessing cumulative watershed effects in the central Sierra Nevada: Hillslope measurements and catchment-scale modeling. In: *Proceedings of the Sierra Science Symposium*. Murphy, D.D., and P.A. Stine (eds.). USDA Forest Service General Technical Report, PSW GTR-193. Pp. 149-158.

MacDonald, L.H., R.W. Sampson, and D.M. Anderson. 2001. Runoff and road erosion at the plot and road segment scale, St. John, U.S. Virgin Islands. *Earth Surface Processes and Landforms* **26**: 1-22.

Megahan, W.F. 1974. Erosion over time: A model. Research paper INT-156, USDA Forest Service, Ogden, UT, USA. 14 pp.

Megahan, W.F., and W.J. Kidd. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. *Journal of Forestry* **70(3)**: 136-141.

Megahan, W.F., S.B. Monsen, and M.D. Wilson. 1991. Probability of sediment yields from surface erosion on granitic roadfills in Idaho. *Journal of Environmental Quality* **20**: 53-60.

Megahan, W.F., Seyedbagheri, K.A., and T.L. Mosko. 1986. Construction phase sediment budget for forest roads in granitic slopes in Idaho. In: *Drainage Basin Sediment Delivery*, Hadley. R.F. (ed.). IAHS Publication 159. Pp. 31-39.

Merz, W., and R.B. Bryan. 1993. Critical conditions for rill initiation on sandy loam brunisols: Laboratory and field experiments in southern Ontario, Canada. *Geoderma* **57**: 357-385.

Mills, K., M. Pyles, and R. Thoreson. 2007. Aggregate surfacing design and management for low-volume roads in temperate, mountainous areas. *Transportation Research Record: Journal of the Transportation Research Board* **1989(2)**: 154-160.

Montgomery, D.R. 1994. Road surface drainage, channel initiation, and slope instability. *Water Resources Research* **30(6)**: 1925-1932.

Petkovšek, G. 2001. RF - A tool for calculation of RUSLE R-factor. <http://ksh.fgg.uni-lj.si/KSH_ANG/introduction/gregor/rf.htm>. Accessed January 2010.

Pietraszek, J. 2006. Controls on post-fire erosion at the hillslope scale, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 124 pp.

Poesen, J.W., D. Torri, and K. Bunte. 1994. Effects of rock fragments on soil erosion by water at different spatial scales: A review. *Catena* **23**: 141-166.

Ramos-Scharrón, C.E., and L.H. MacDonald. 2005. Measurement and prediction of sediment production from unpaved roads, St John, US Virgin Islands. *Earth Surface Processes and Landforms* **30**: 1283-1304.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agricultural Handbook No 703, Washington, D.C., USA. 324 pp.

Reid, L.M., and T. Dunne. 1984. Sediment production from forest road surfaces. *Water Resources Research* **20(11)**: 1753-1761.

Rivera, S., J.L. Kershner, and G.R. Keller. 2009. Testing road surface treatments to reduce erosion in forest roads in Honduras. *Ciencia e Investigación Agraria* **36(3)**: 425-432.

Robichaud, P.R., and R.E. Brown. 2002. Silt fences: An economical technique for measuring hillslope soil erosion. USDA Forest Service, RMRS-GTR-94, Fort Collins, CO, USA. 24 pp.

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

Sugden, B.D., and S.W. Woods. 2007. Sediment production from forest roads in Western Montana. *Journal of the American Water Resources Association* **43(1)**: 193-206.

Swift Jr., L.W. 1988. Forest access roads: Design, maintenance, and soil loss. In: *Forest Hydrology and Ecology at Coweeta.* Swank, W.T., and D.A. Crosley, Jr. (eds.), Springer-Verlag, NY, USA. Pp. 313-324.

USDA Forest Service. 1983. Soil survey of Sierra National Forest area, California. USDA Forest Service, Pacific Southwest Region: Auberry, Cascadel Point, Musick Mtn., and Shaver Lake Quadrangles. 1:24,000. 7.5 Minute Series.

Weaver, W., and D. Hagans. 1999. Storm-proofing forest roads. In: *Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium*: OSU Department of Forest Engineering and International Union of Forestry Research Organizations, Corvallis, OR, USA. Pp. 230-245.

Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. *Water Resources Bulletin* **32**: 1195-1207.

Welsh, M.J. 2008. Sediment production and delivery from forest roads and off-highway vehicle trails in the Upper South Platte River watershed, Colorado. M.S. thesis, Colorado State University, Fort Collins, CO, USA. 154 pp.

Ziegler, A.D., and T.W. Giambelluca. 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. *Journal of Hydrology* **196**: 204-229.

Ziegler, A.D., T.W. Giambelluca, R.A. Sutherland, M.A. Nullet, S. Yarnasarn, J. Pinthong, P. Preechapanya, and S. Jaiarree. 2004. Toward understanding the cumulative impacts of roads in upland agricultural watersheds of northern Thailand. *Agricultural Ecosystem Environments* **104**: 145-158.

Ziegler, A.D., R.A. Sutherland, and T.W. Giambelluca. 2000. Partitioning total erosion on unpaved roads into splash and hydraulic components: The roles of interstorm surface preparation and dynamic erodibility. *Water Resources Research* **36(9)**: 2787-2791.

Ziegler, A.D., R.A. Sutherland, and T.W. Giambelluca. 2001. Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads. *Earth Surface Processes and Landforms* **26**: 235-250.

3.8. Tables

Table 3.1. Number of native, gravel, and mixed surface road segments and ditches adjacent to paved roads that were monitored for sediment production in the Providence Creek watersheds from WY2004 to WY2009.

	Water year						
	2004	2005	2006	2007	2008	2009	Totals
Native surface road segments	11	13	13	6	6	6	55
Gravel surface road segments	7	7	7	7	7	7	42
Mixed surface road segments	4	4	4	4	4	4	24
Ditches adjacent to paved roads	7	7	7	7	7	7	42

Table 3.2. Number of native, gravel, and graded road segments in José Basin with valid sediment production values in WY2008 and WY2009.

	Water year		
	2008	2009	Totals
Native surface road segments	13	30	43
Gravel surface road segments	5	11	16
First year post-grading	3	24	27
Second year post-grading	0	3	3

Table 3.3. Road segment characteristics measured, estimated, or observed for each segment with a sediment fence and the surveyed road segments. /E indicates that the characteristic was estimated rather than measured in the surveys conducted on segments that were not monitored for sediment production.

Characteristic	**Measured (M), estimated (E), or observed (O)**	**Continuous (C) or categorical group (G)**	**Method of measurement**
Length (m)	M	C	Meter wheel
Surface type (Native, Gravel)	O	G	
Active width (m)	M	C	Cloth tape
Total width (m)	M	C	Cloth tape
Slope (%)	M	C	Clinometer
Bare soil (%)	M / E	C	Cover count
Gravel cover (%)	M / E	C	Cover count
Traffic level (Very low, Low, Medium)	E	G	
Evidence of past surface rocking (Y/N)	O	G	
Cutslope height (m)	E	C	
Cutslope gradient (%)	M	C	Clinometer
Cutslope percent bare soil (%)	E	C	
Slope of upper hillslope (%)	M	C	Clinometer
Slope of lower hillslope (%)	M	C	Clinometer
Ditch width (m)	M	C	Cloth tape
Ditch slope (%)	M	C	Clinometer
Rill length (m)	M	C	Cloth tape
Rill width (m)	M	C	Ruler
Rill depth (m)	M	C	Ruler
Drain type (see Table 3.4)	O	G	
Drain feature (see Table 3.4)	O	G	
Drain armoring (Y/N)	O	G	
Water cross armoring (Y/N)	O	G	
Armoring buried (Y/N)	O	G	
Armoring intact (Y/N)	O	G	
Pushout present (Y/N)	O	G	
Pushout effective (Y/N)	O	G	
Fillslope erosion (Y/N)	O	G	
Maximum fillslope rill depth (m)	M	C	Ruler
Multiple fillslope rills (Y/N)	O	G	
Drainage feature length (m)	M	C	Cloth tape
Drainage feature slope (%)	M	C	Clinometer
Drainage feature roughness (1,2,3,4)	O	C	
Connectivity class (1,2,3,4)	O	G	
Culvert present (Y/N)	O	G	
Culvert plugged (%)	E	C	
Scour at culvert outlet (Y/N)	O	G	
Volume of scour at culvert outlet (m^3)	M	C	Cloth tape

Table 3.4. Drain type and drain feature categories used to describe each road segment. Slashes indicate a mixture of types or features within a road segment where flow was restricted to one discrete drainage point by berms and/or the cutslope.

Drain types	**Drain features**
Insloped	Diffuse
Outsloped (diffuse)	Dip
Outsloped (with a berm)	Pushout
Planar	Waterbar
Through cut	Stream crossing
Insloped/Planar	Cattle guard
Insloped/Outsloped with a berm	On segment deposition
Outsloped with a berm/Planar	Intersection
Planar/Outsloped	Diffuse/Dip
Insloped/Outsloped/Planar	Diffuse/Waterbar
	Diffuse/Pushout
	Diffuse/Intersection
	Diffuse/On segment deposition
	Dip/Pushout
	Dip/On segment deposition
	Cattle guard/Pushout
	Intersection/On segment deposition

Table 3.5. Definition of each connectivity class and the associated potential for runoff and sediment to be delivered to the stream network.

Connectivity class	Definition	Potential for sediment delivery
1	Drainage feature <10 m long.	Very low
2	Drainage feature <20 m long.	Low/moderate
3	Drainage feature >20 m long but more than 10 m from a stream channel.	Moderate/high
4	Drainage feature to within 10 m of a stream channel, regardless of length.	High

Table 3.6. Elevation and annual precipitation and erosivity for the functioning rain gages in José Basin in WY2008 and WY2009. – indicates that the gage did not collect valid data for that water year.

Rain gage	Elevation (m)	Precipitation (mm)		Erosivity (MJ ha^{-1} mm hr^{-1})	
		WY2008	WY2009	WY2008	WY2009
JRG1	1050	462	--	674	--
JRG2	1100	581	403	732	160
JRG3	1120	501	--	522	--
JRG4	1250	--	677	--	568
JRG5	1000	533	582	603	449
Mean (s.d.)	1100 (90)	519 (50)	554 (139)	633 (91)	393 (210)

Table 3.7. Correlation coefficients, coefficients of determination, and p values for the regressions between key site variables and annual sediment production from gravel surface road segments in José Basin. Values in bold are significant at $p \leq 0.10$.

Variable	**r**	**R^2**	**p value**
Length (m)	-0.40	0.17	0.12
Area (m^2)	-0.42	0.17	0.11
Slope (%)	**-0.48**	**0.23**	**0.06**
Area*slope (m^2)	**-0.54**	**0.29**	**0.03**
Percent bare soil	**0.48**	**0.23**	**0.06**
Percent gravel cover	-0.05	0.00	0.90
Elevation (m)	-0.40	0.16	0.13
Annual precipitation (mm)	**0.44**	**0.20**	**0.08**
Erosivity (MJ ha^{-1} mm hr^{-1})	**0.67**	**0.45**	**<0.01**
Rill length (m)	-0.37	0.14	0.15
Rill volume (m^3)	-0.29	0.09	0.27

Table 3.8. Significance of the variables in the multivariate model for predicting sediment production from gravel surface road segments in José Basin.

Variable	**p value**
Annual erosivity (MJ ha^{-1} mm hr^{-1})	0.0003
Segment area (m^2)	0.0004
Segment slope (%)	0.0008
Segment area*slope (m^2 m m^{-1})	0.0014

Table 3.9. Mean sediment production rate, road length, mean width, and proportion of the road surface directly connected to the stream network for native, gravel, mixed surface roads, and road ditches in the Providence Creek watersheds. *The potential sediment delivered and the proportion of total potential delivered sediment in José Basin were predicted by the multivariate models, rather than by using mean sediment production rates.

	Mean sediment production rate (kg m^{-2} yr^{-1})	**Road length (km)**	**Mean road width (m)**	**Proportion connected**	**Potential sediment delivery (kg yr^{-1})**	**Proportion of total potential delivered sediment**
Providence Creek watersheds						
Native surface roads	0.78	7.6	2.2	0.04	470	0.35
Gravel surface roads	0.16	1.5	2.3	0.11	60	0.04
Mixed surface roads	0.35	2.8	2.6	0.31	800	0.59
Ditches adjacent to paved roads	0.02	2.1	3.5	0.16	20	0.02
Total sediment contribution from roads					*1,350*	
José Basin						
Native surface roads	1.7	67	2.6	0.30	210,000	0.88
Gravel surface roads	1.6	29	2.6	0.40	30,000	0.13
Total sediment contribution from roads					*240,000*	

Table 3.10. Characteristics of and sediment production rates for the six matched pairs of ungraded and graded road segments in José Basin.

Road segment	**Ungraded or Graded**	**Length (m)**	**Width (m)**	**Area (m^2)**	**Slope (%)**	**A*S**	**Percent bare soil**	**Percent gravel**	**Sediment production rate ($kg\ m^{-2}\ yr^{-1}$)**
JNH5	Ungraded	36	2.5	89	12	1068	66	1	0.0
JNH4	Graded	44	2.6	114	13	1482	84	2	4.1
JPS15	Ungraded	31	2.7	84	4	336	73	0	0.2
JPS16	Graded	45	3.4	153	5	765	94	0	0.7
JPS18	Ungraded	70	2.4	168	8	1344	46	0	0.1
JPS17	Graded	85	2.4	204	10	2040	78	0	0.6
JPS19	Ungraded	28	2.5	70	10	700	49	0	0.2
JPS20	Graded	16	2.7	43	10	430	94	0	0.8
JPS21	Ungraded	28	2.2	62	10	620	54	1	0.3
JPS22	Graded	32	2.8	90	10	900	82	1	3.0
JNH11	Ungraded	30	3	90	10	900	73	10	0.4
JPS23	Graded	29	2.7	78	13	1014	73	13	1.7
Mean (s.d.)	**Ungraded**	**37 (16)**	**2.6 (0.3)**	**94 (38)**	**9 (3)**	**828 (355)**	**60 (12)**	**2 (4)**	**0.2 (0.1)**
	Graded	**42 (24)**	**2.8 (0.3)**	**114 (58)**	**10 (3)**	**1105 (572)**	**84 (8)**	**3 (5)**	**1.8 (1.4)**

Table 3.11. Segment and rill characteristics for 119 unrilled road segments and 53 rilled road segments one year after grading, and the p values for each comparison.

	Segment length (m)	**Segment slope (%)**	**Percent bare**	**Percent gravel**	**Drainage feature length (m)**	**Ineffective bars/dips per km**	**Rill length (m)**	**Rill volume (m^3)**
No rills present (5,144 m)								
Mean	43	8	82	14	10	2.3	--	--
s.d.	27	4	19	18	14		--	--
Rills present (2,934 m)								
Mean	55	11	86	7	17	5.5	19	0.22
s.d.	45	4	12	11	15		28	0.41
p values	0.03	0.0004	0.19	0.02	0.01		--	--

Table 3.12. Rill volume, bulk density, rill erosion, measured sediment production, and the ratio of rill erosion relative to the mass of sediment collected in the sediment fence. All segments were graded one year earlier, and NA indicates that no rill erosion was present.

Year graded	**Road segment**	**Rill volume (m^3)**	**Bulk density ($g\ cm^{-3}$)**	**Rill mass (kg)**	**Sediment production (kg)**	**Ratio of rill erosion to sediment production**
2008	JBT8	0.12	1.69	196	428	0.46
	JBT9	0.18	1.74	319	658	0.48
2009	JBT1	0.04	1.66	66	89	0.74
	JBT2	0.81	1.66	1344	1025	1.31
	JBT3	0.08	1.79	141	470	0.30
	JBT4	0.1	1.79	178	818	0.22
	JBT5	0.21	1.8	380	622	0.61
	JBT6	0.07	1.3	87	76	1.14
	JBT7	0.17	1.57	260	831	0.31
	JBT11	0.91	1.56	1421	2480	0.57
	JBT12	0.7	1.32	922	433	2.13
	JBT13	NA	1.38	NA	258	NA
	JBT14	0.11	1.38	157	333	0.47
	JBT17	0.46	2.34	1089	862	1.26
	JBT18	3.05	1.37	4184	1375	3.04
	JBT19	4.44	1.61	7140	1549	4.61
	JBT20	NA	1.75	NA	201	NA
	JBT21	0.34	1.33	456	1090	0.42
	JNH4	0.06	1.35	84	367	0.23
	JNH6	0.14	1.35	189	553	0.34
	JNU1	NA	1.29	NA	10	NA
	JNU2	NA	1.59	NA	115	NA
	PS16	0.01	1.16	16	103	0.16
	PS17	NA	1.43	NA	132	NA
	PS20	NA	1.43	NA	34	NA
	PS22	0.06	1.67	99	269	0.37
	PS23	0.04	1.52	55	136	0.40
Mean		**0.58**	**1.55**	**894**	**567**	**0.93**
s.d.		**1.11**	**0.24**	**1706**	**565**	**1.10**

3.9. Figures

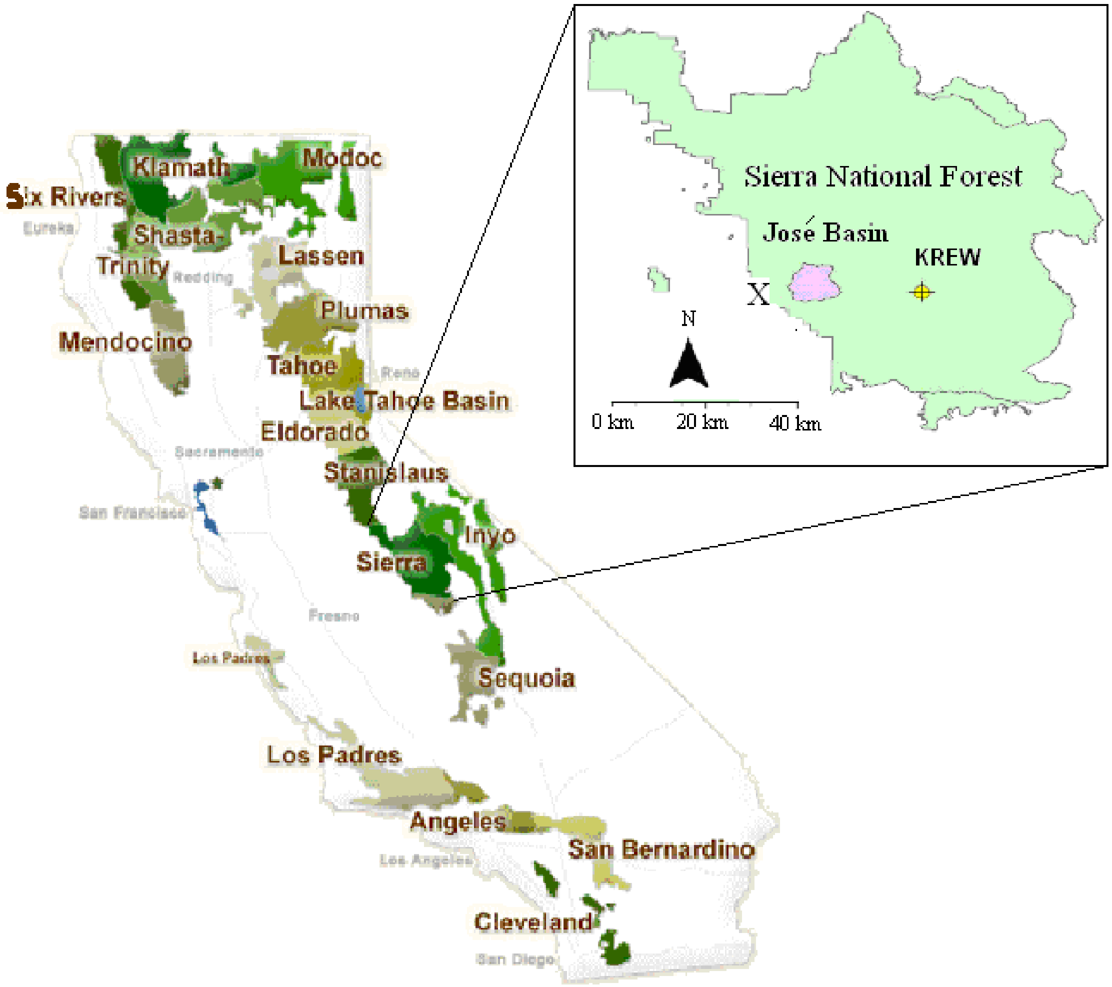

Figure 3.1. Location of the national forests in California, including the Eldorado and the Sierra National Forest (SNF). Inset is Sierra National Forest, showing José Basin and the Kings River Experimental Watersheds (KREW). X indicates the location of the Auberry precipitation gage (CA map from http://www.fs.fed.us/r5/forests.shtml).

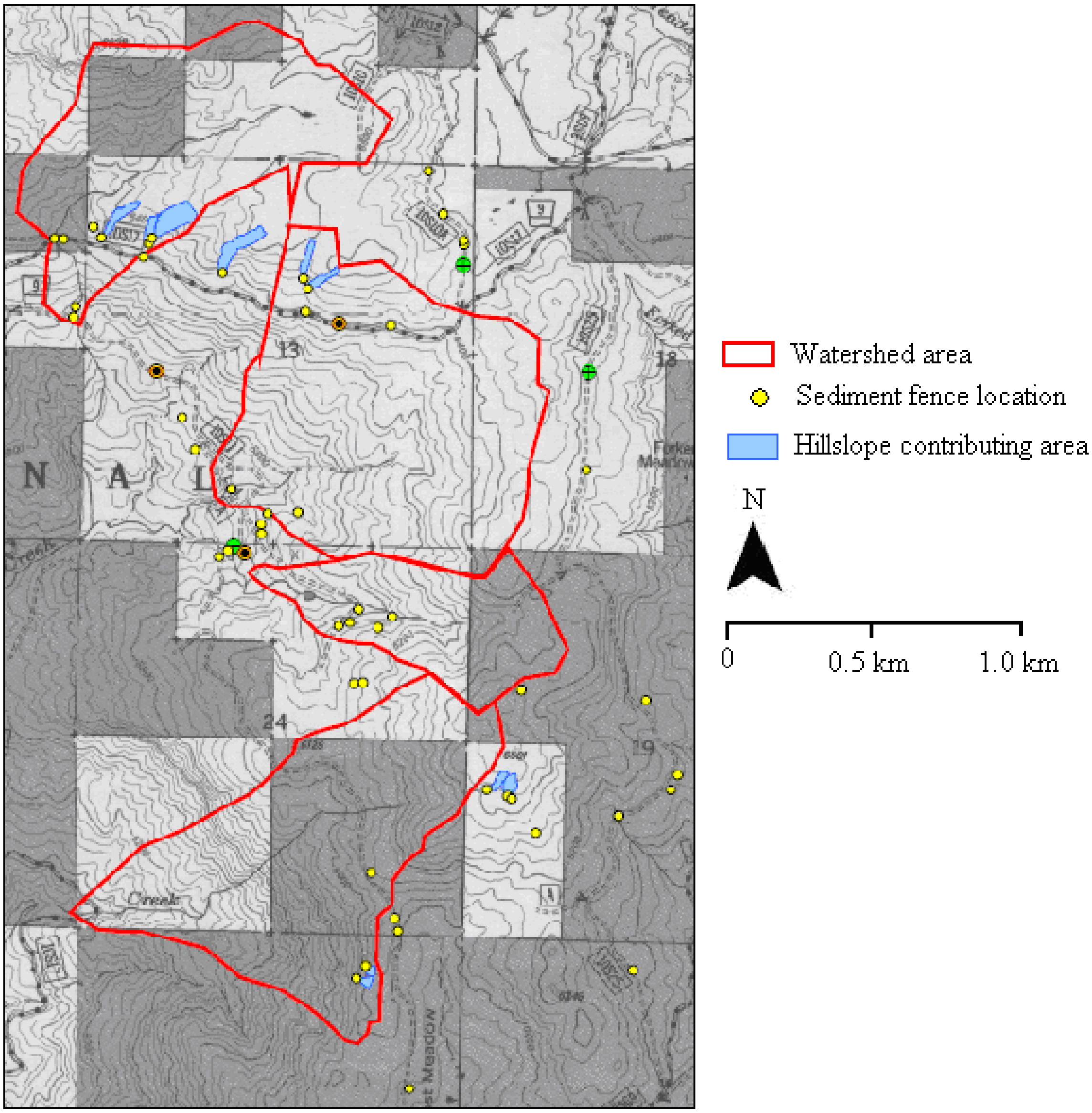

Figure 3.2. Map of the four Providence Creek watersheds in the Kings River Experimental Watersheds (KREW) and the sediment fences used to monitor hillslope and road sediment production. Contributing areas for the hillslope sediment fences are shown in blue. The sediment fences along the main east-west road in the upper part of the map are measuring sediment production from the ditches adjacent to this insloped, paved road. (Map courtesy A. Korte).

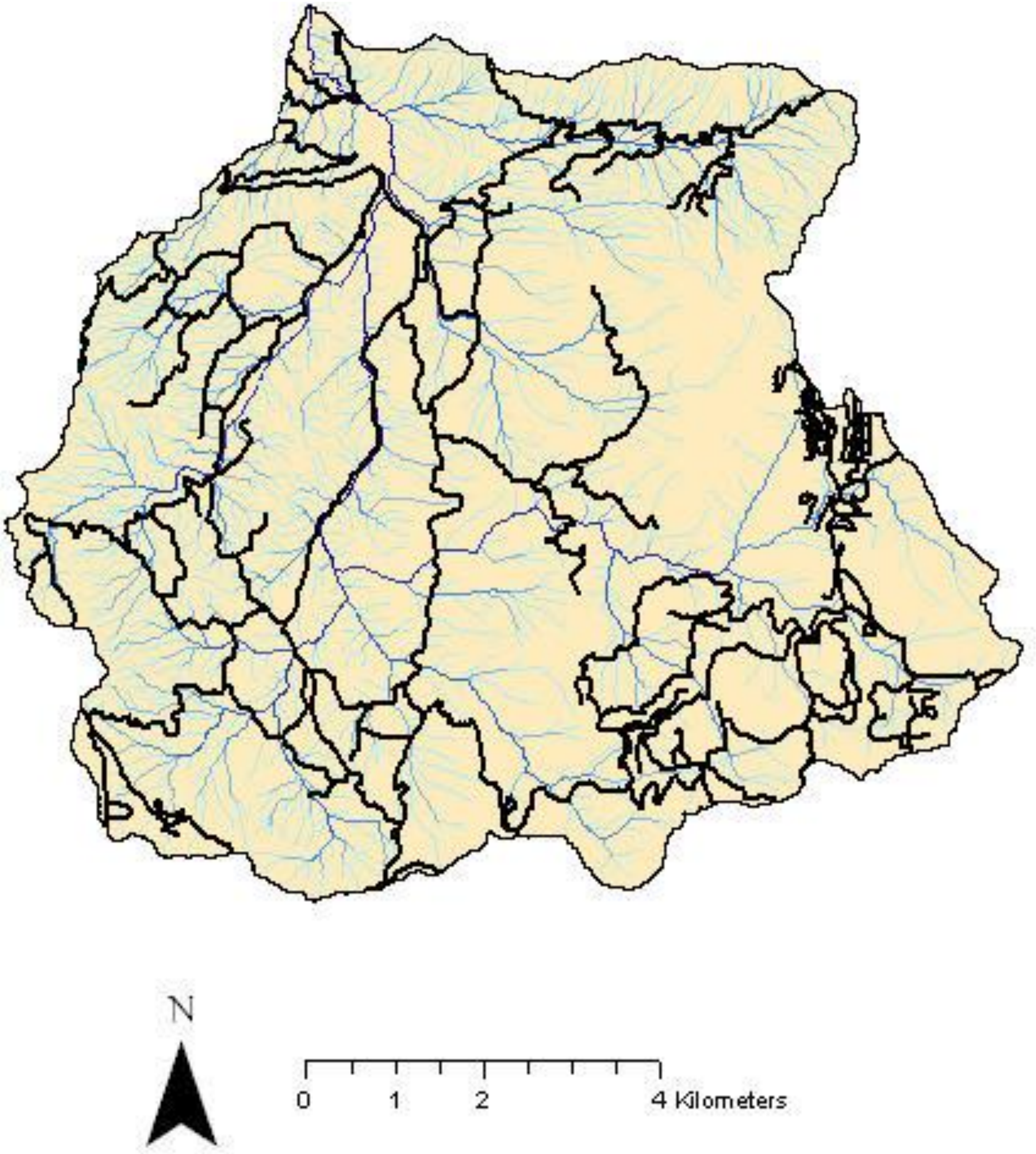

Figure 3.3. Roads (in black) and streams (in blue) in José Basin.

Figure 3.4. One or more sediment fences were installed at the drainage point of road segments in José Basin and the Providence Creek watersheds. The fence in the foreground was installed in summer 2007 in José Basin just below a waterbar draining a native surface road segment, and the second fence was added in summer 2008 to prevent overtopping.

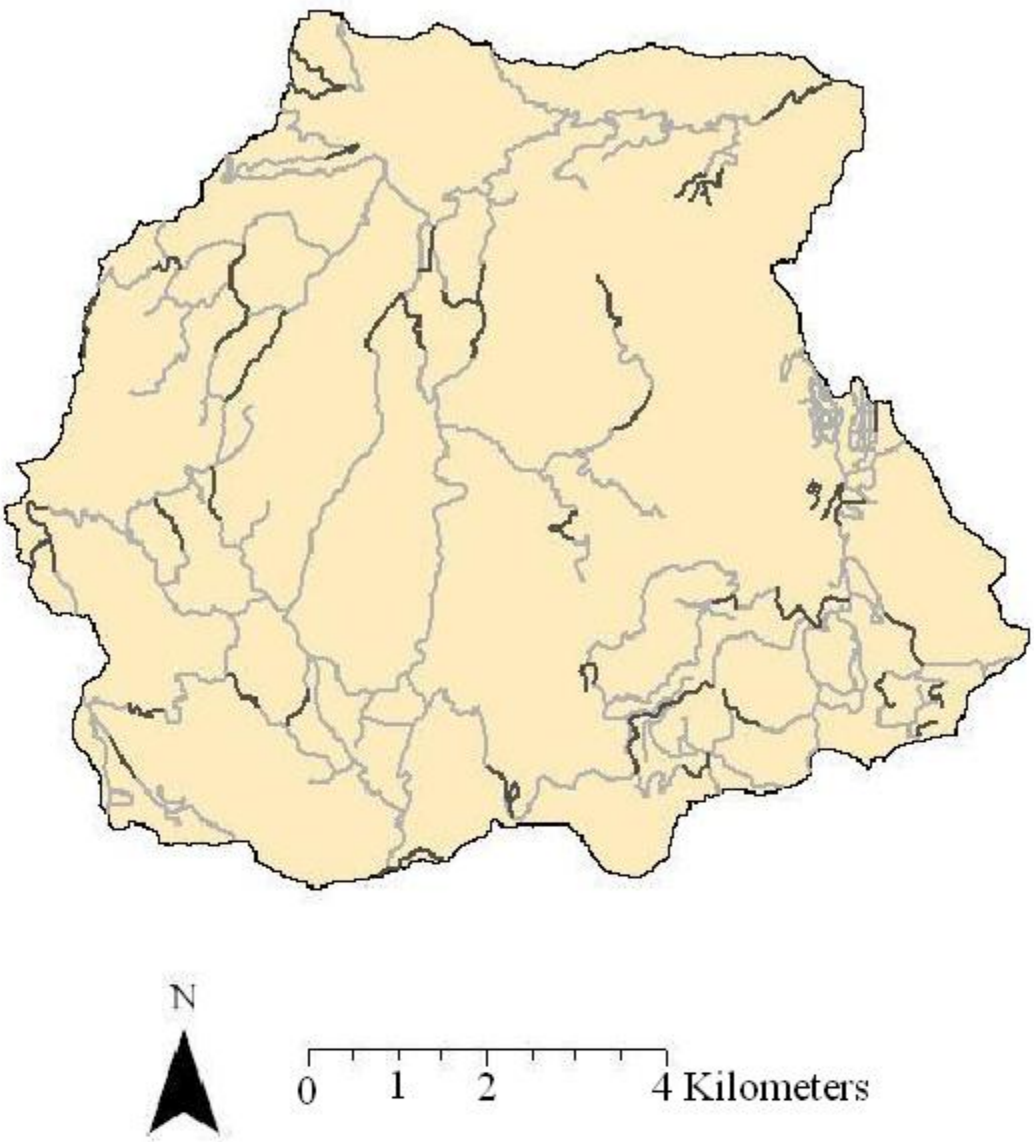

Figure 3.5. Twenty percent of the road network in José Basin was randomly selected and surveyed. Selected sections are black and the remainder of the road network is shown in grey.

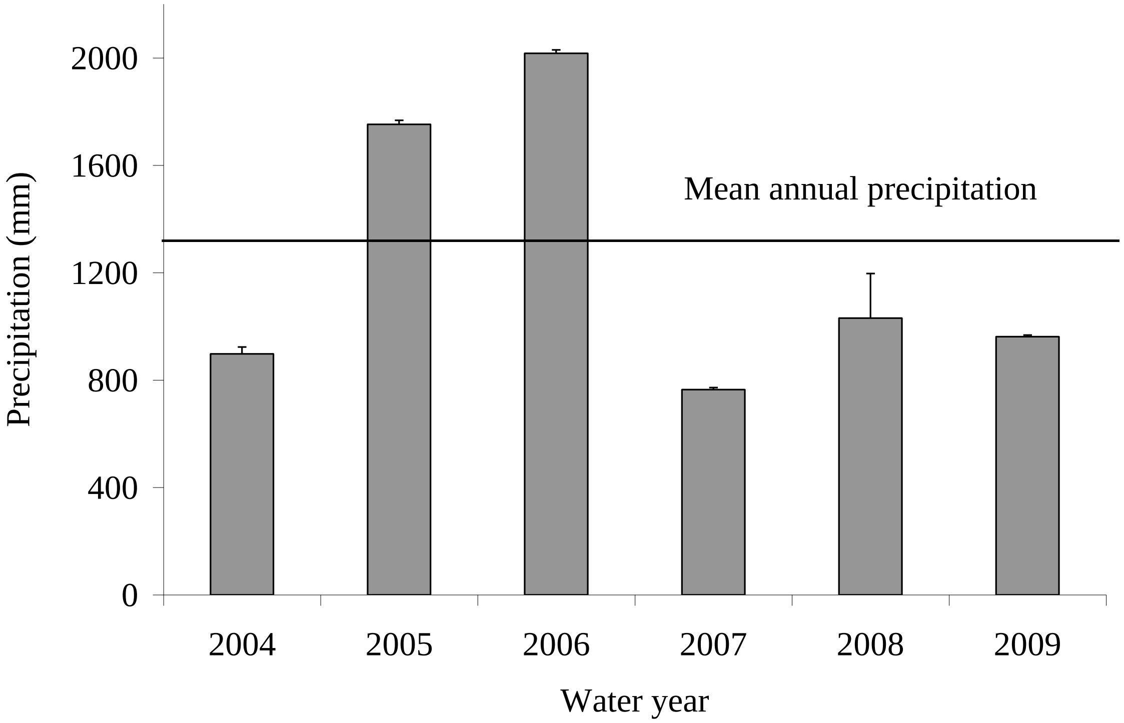

Figure 3.6. Mean annual precipitation for the Providence Creek watersheds for WY2004 to WY2009. Error bars represent one standard deviation.

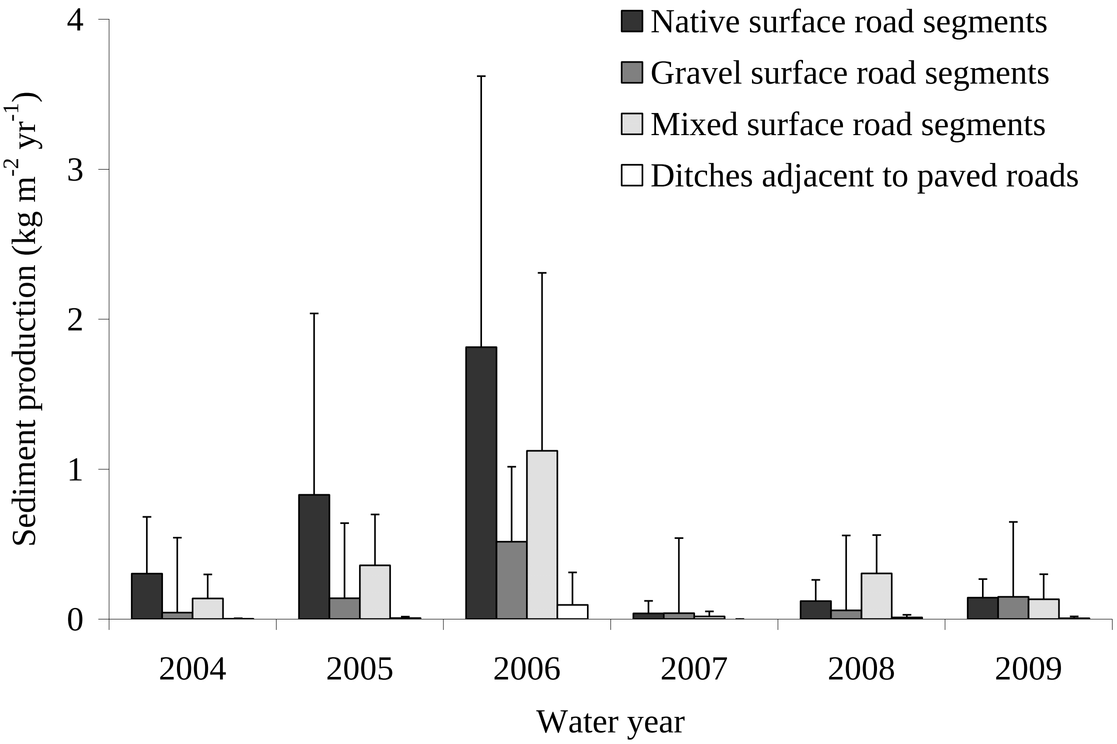

Figure 3.7. Mean annual sediment production in the Providence Creek watersheds for WY2004 through WY2009 for native, gravel, and mixed surface road segments as well as ditches adjacent to paved, insloped road segments. Error bars represent one standard deviation.

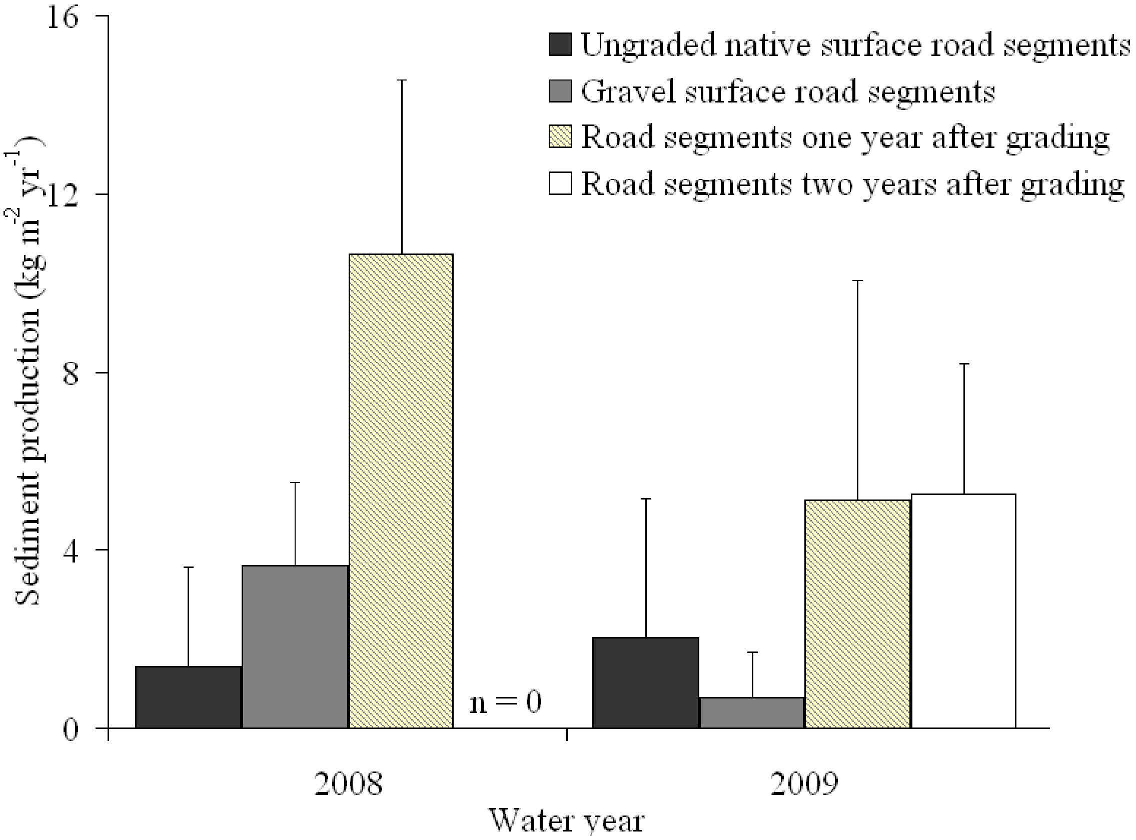

Figure 3.8. Mean sediment production rates in José Basin for WY2008 and WY2009 for ungraded native surface road segments, gravel surface road segments, and road segments one and two water years after grading, respectively. Error bars indicate one standard deviation.

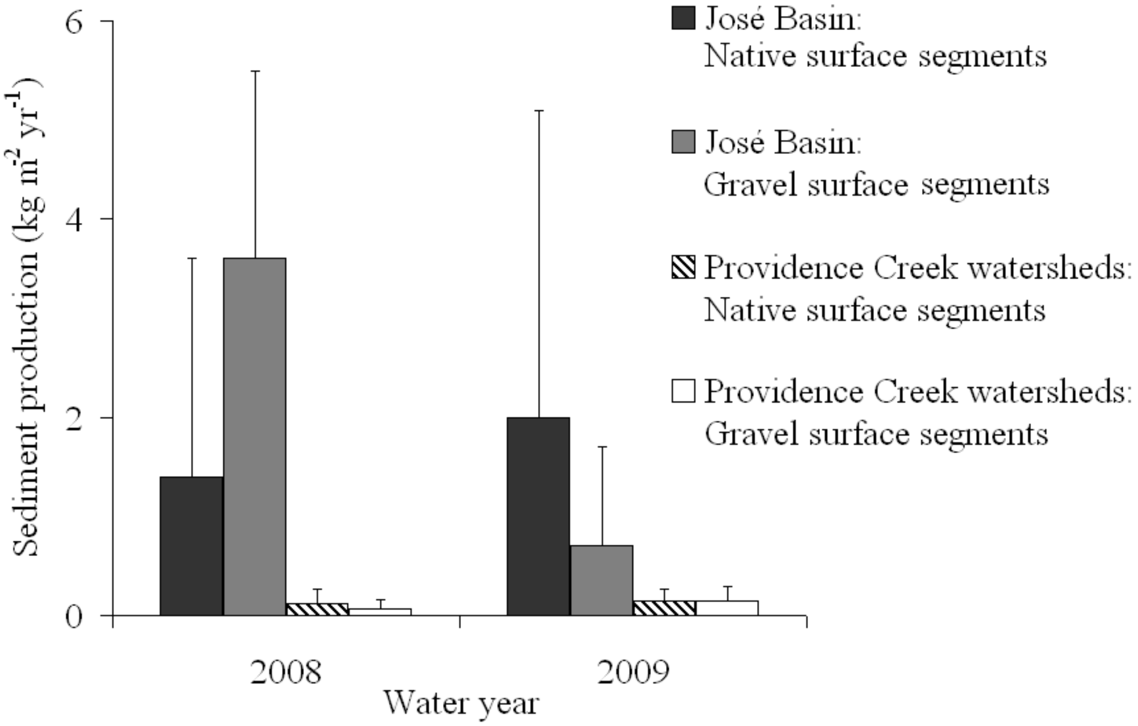

Figure 3.9. Mean sediment production rate for native and gravel surface road segments in José Basin and the Providence Creek watersheds for WY2008 and WY2009. Error bars indicate one standard deviation.

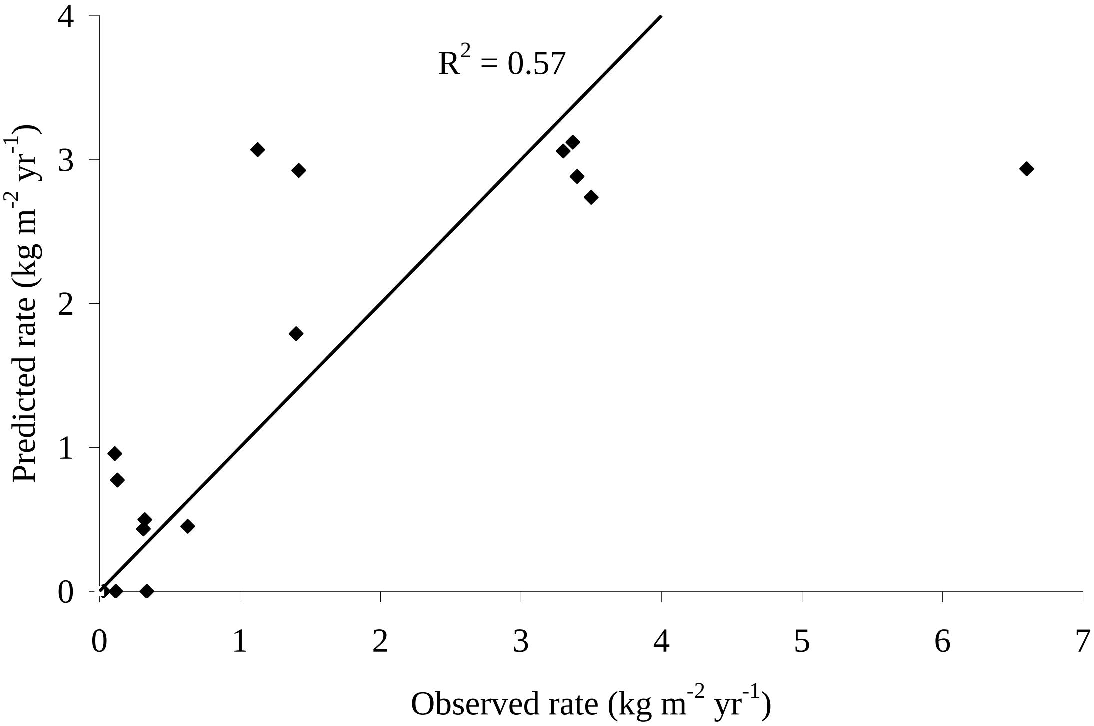

Figure 3.10. Observed versus predicted sediment production rates (kg m^{-2} yr^{-1}) for gravel surface segments in José Basin. Line shows a 1:1 relationship.

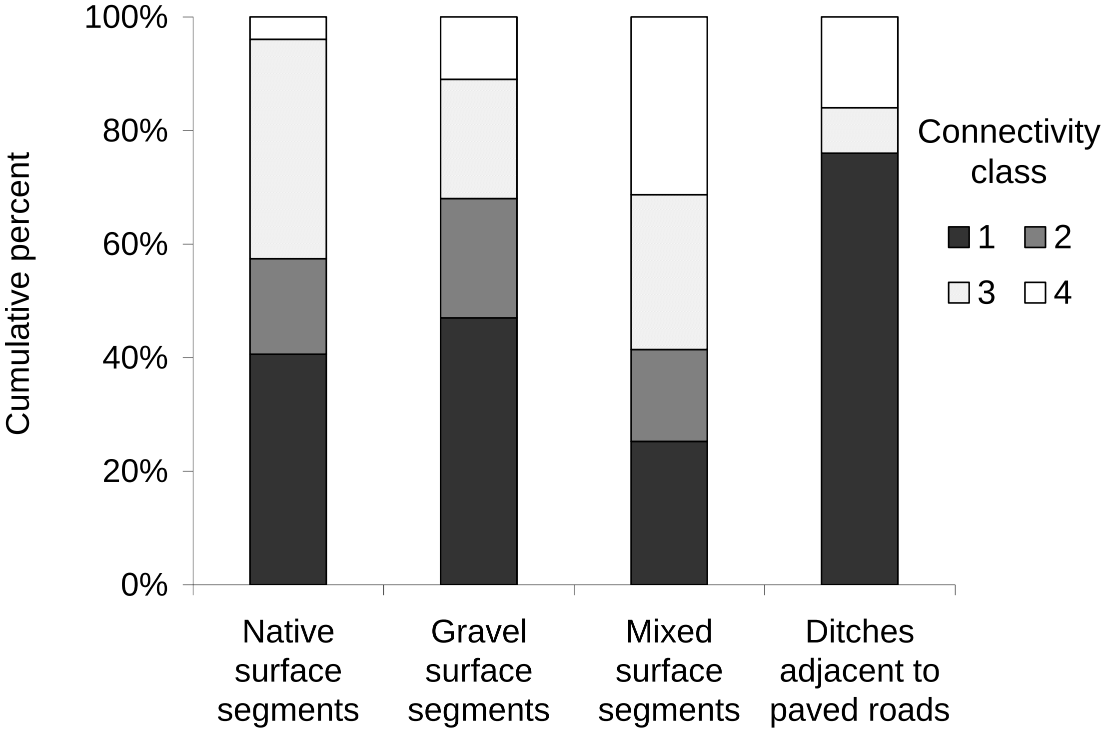

Figure 3.11. Hydrologic connectivity classes for native, gravel, and mixed surface road segments in the Providence Creek watersheds as well as ditches adjacent to paved roads. 1 indicates a drainage feature less than 10 m long and at least 10 m from a stream channel, and 4 indicates that a segment is connected to the stream channel.

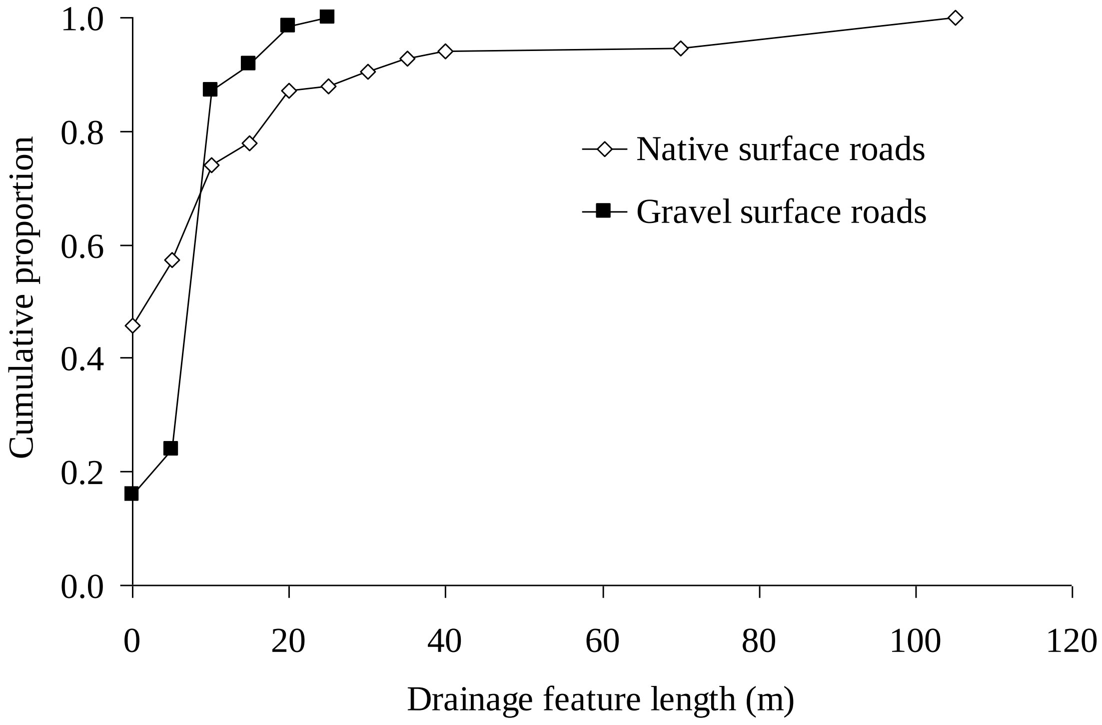

Figure 3.12. Cumulative proportion of road length versus drainage feature length for native and gravel surface roads in José Basin.

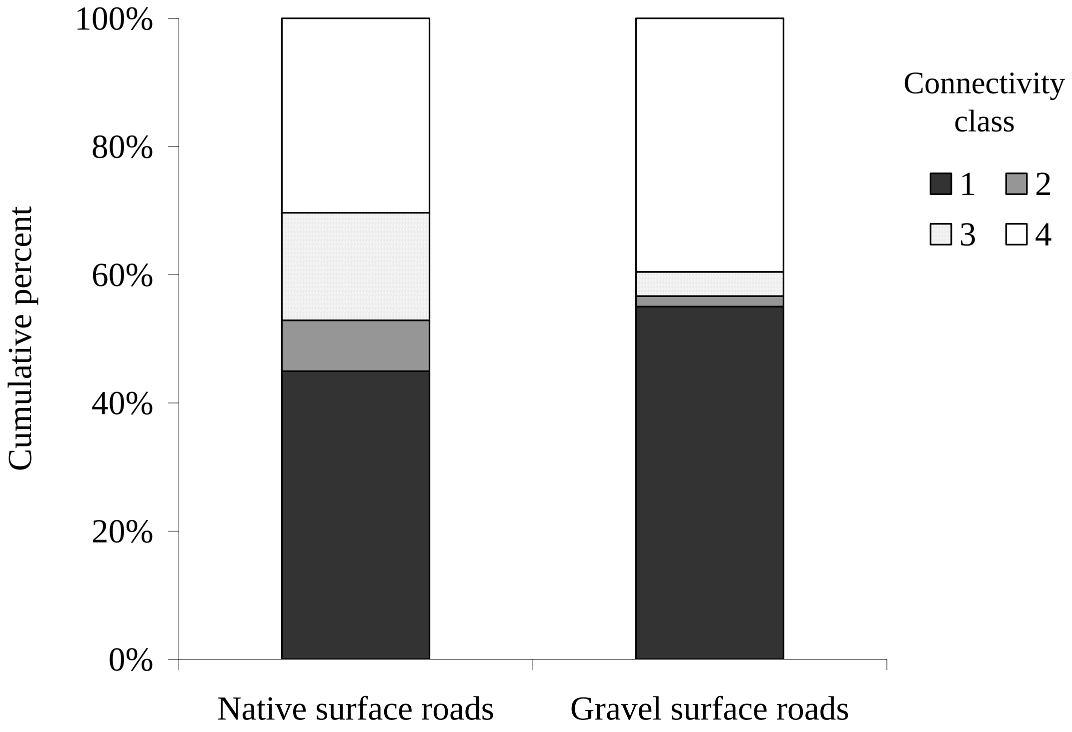

Figure 3.13. Hydrologic connectivity classes for native and gravel surface roads in José Basin. 1 indicates a drainage feature less than 10 m long and at least 10 m from a stream channel, and 4 indicates a segment is connected to the stream channel.

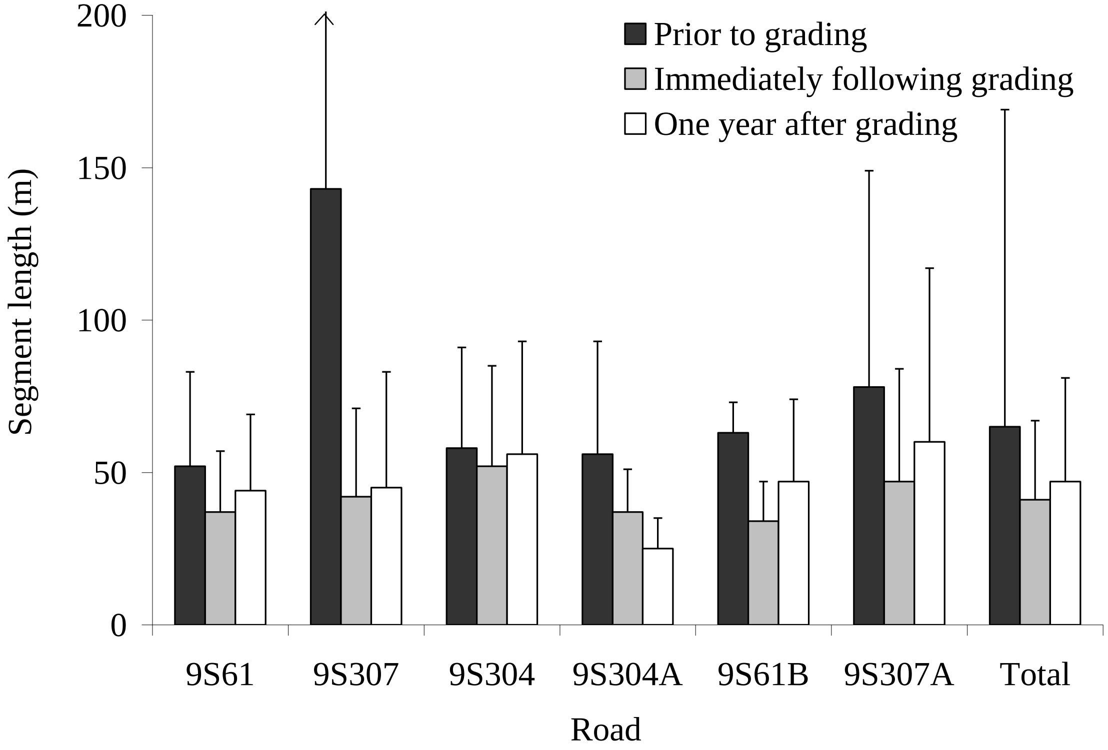

Figure 3.14. Mean segment lengths for six roads in José Basin prior to grading, immediately after grading, and one water year after grading. Error bars indicate one standard deviation. The standard deviation on 9S307 prior to grading was 300 m.

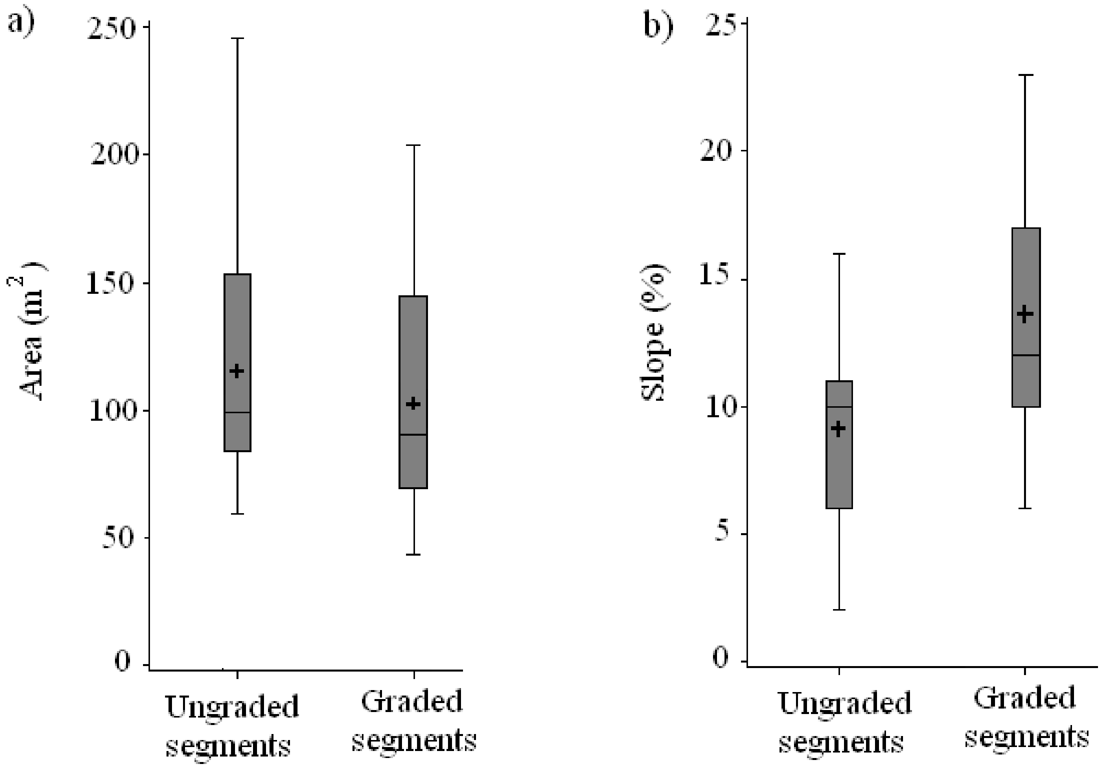

Figure 3.15. Box and whisker plots of a) segment areas and b) segment slopes for the ungraded and graded road segments with valid sediment production data in José Basin. Boxes represent the 25% and 75% quartiles, lines represent the medians, plus signs represent the means, and the whiskers represent minimums and maximums.

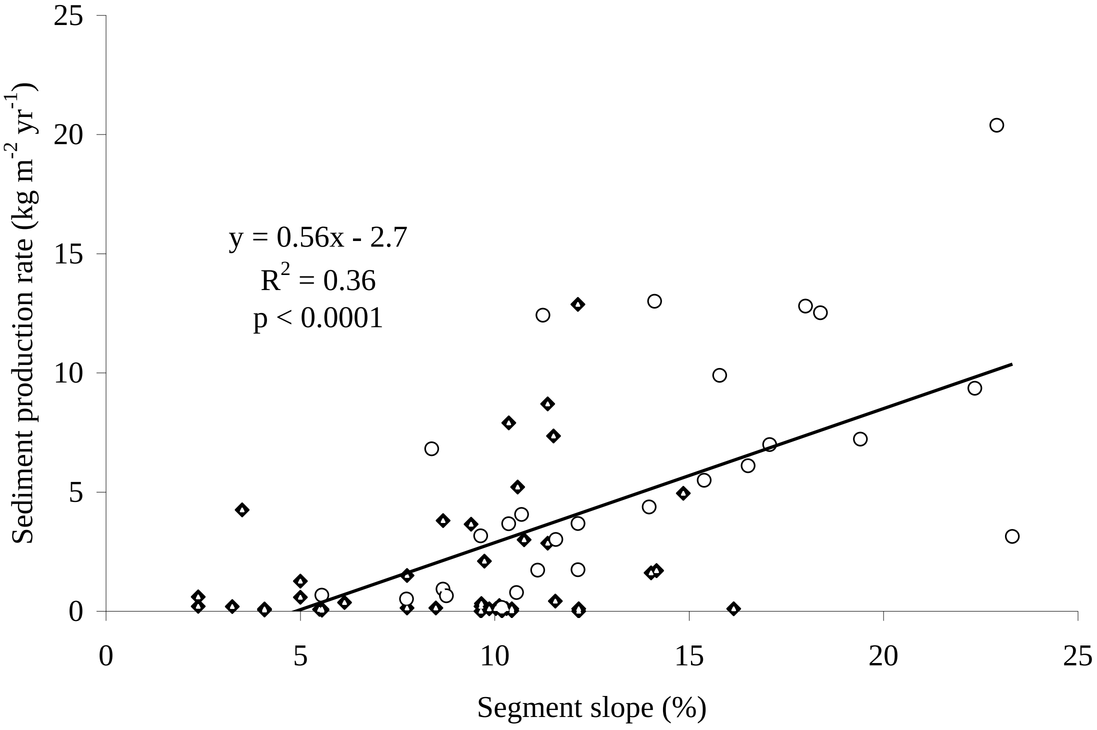

Figure 3.16. Annual sediment production versus segment slope for the ungraded and graded native surface segments in José Basin for WY2008 and WY2009.

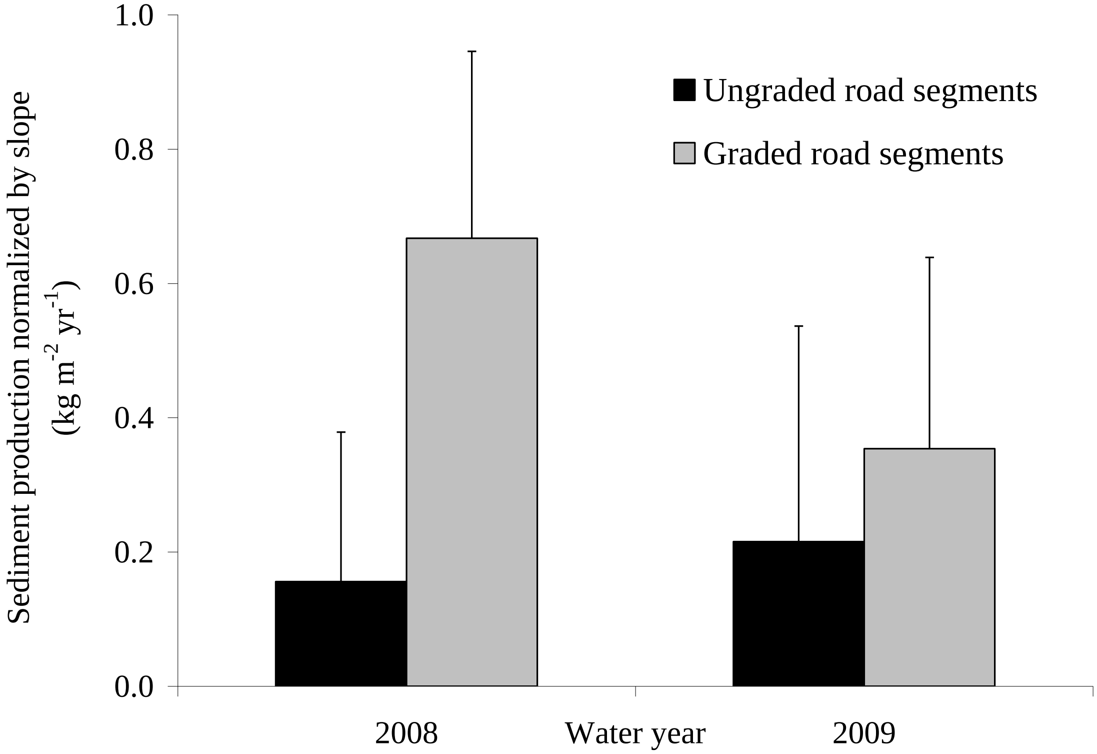

Figure 3.17. Mean sediment production rates normalized by slope for ungraded and graded segments in WY2008 and WY2009. The differences were significant for both WY2008 ($p = 0.01$) and WY2009 ($p = 0.04$).

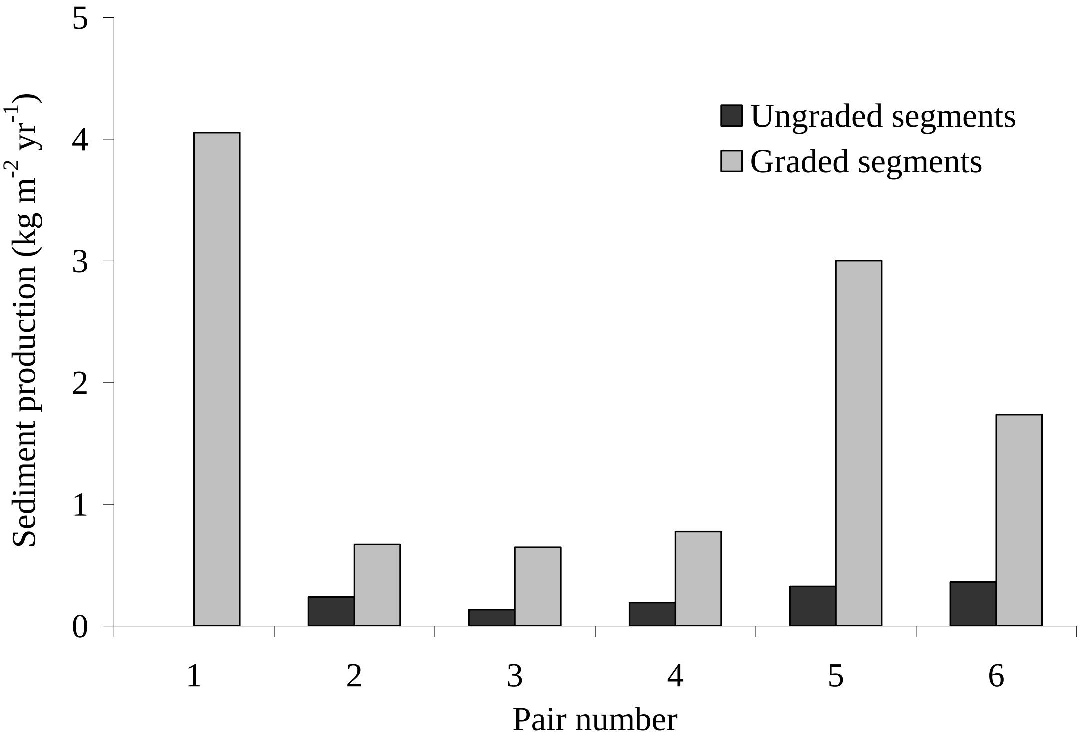

Figure 3.18. Sediment production for WY2009 for each of the six matched pairs of ungraded and graded segments in José Basin.

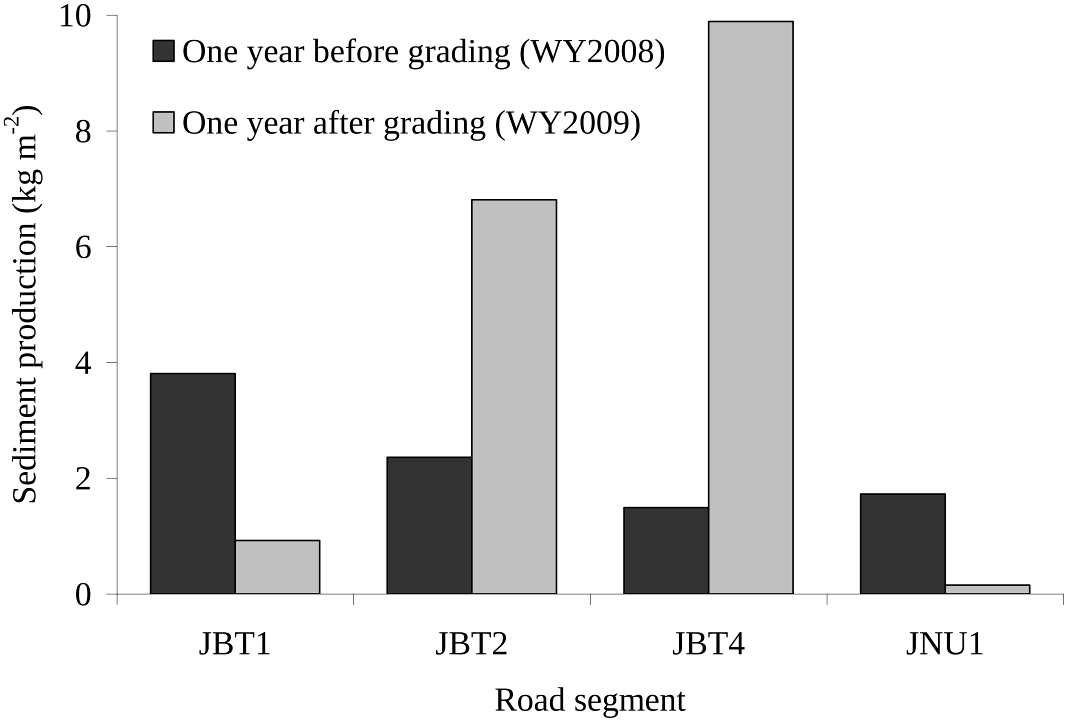

Figure 3.19. Annual sediment production for four segments in José Basin for the year prior to grading (WY2008) and the year after grading (WY2009).

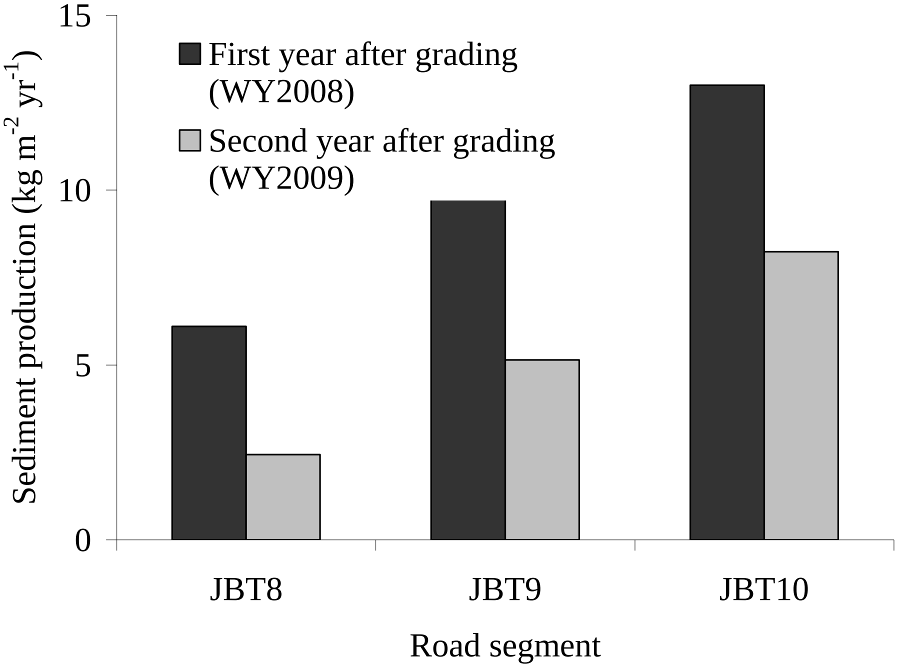

Figure 3.20. Sediment production rates in the first and second water year after grading for three segments in José Basin.

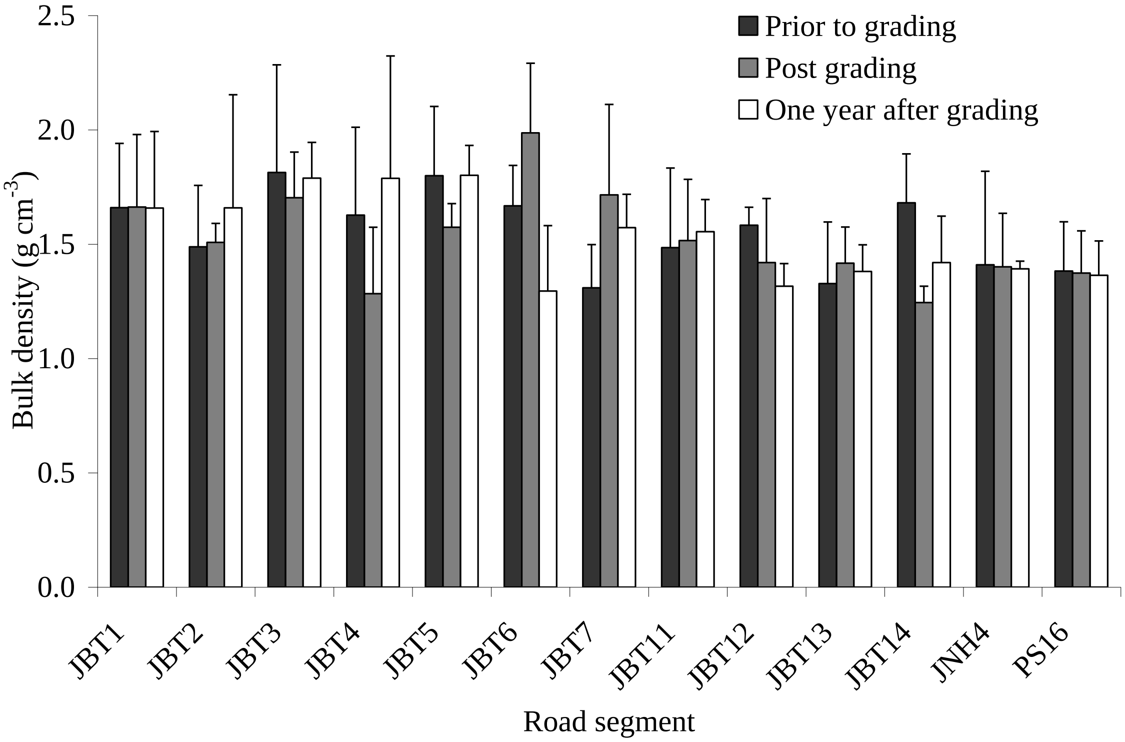

Figure 3.21. Mean bulk density for 13 road segments prior to grading, immediately after grading, and one year after grading. Error bars display one standard deviation.

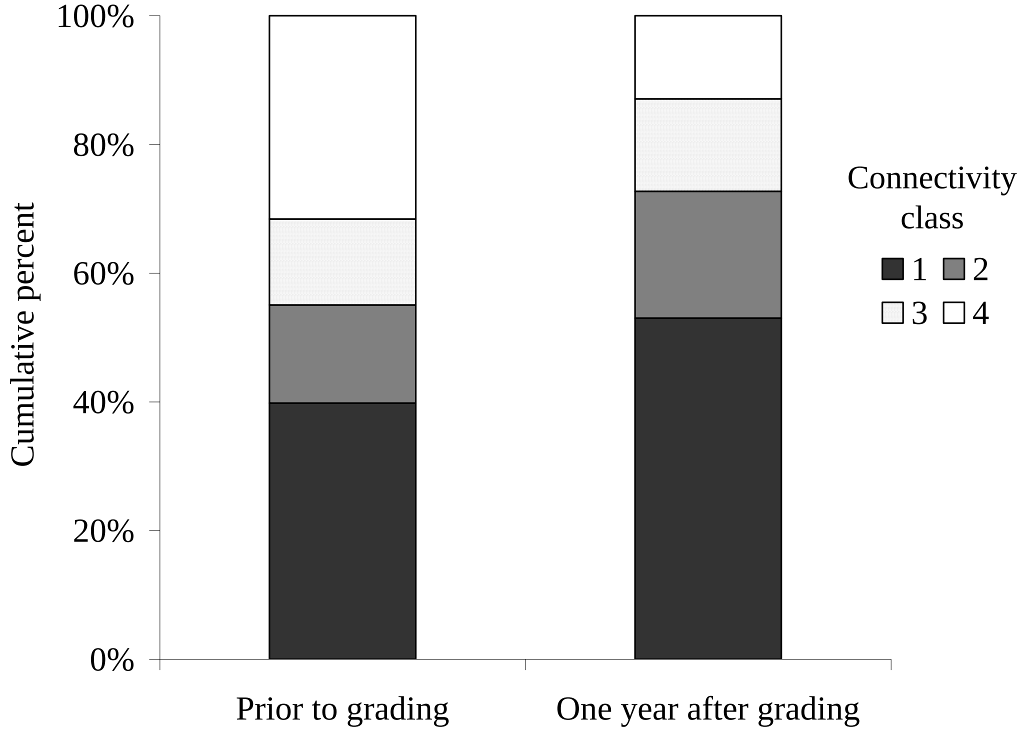

Figure 3.22. Hydrologic connectivity classes for six kilometers of road in José Basin prior to grading and one year after grading. 1 indicates a drainage feature less than 10 m long and at least 10 m from a stream channel, and 4 indicates a segment is connected to the stream channel.

5. Appendices

Appendix A. Characteristics and sediment production rates for hillslopes in José Basin by soil type.

Hillslope	Axis length (m)	Area (m^2)	Axis slope (%)	Mean side slope (%)	Fence elevation (m)	Sediment production rate ($kg\ m^{-2}\ yr^{-1}$)	
Hillslopes in Holland soil						**WY2008**	**WY2009**
JHS4	117	5500	25	11	1037	0.0002	0.0000
JHS7	84	3200	38	20	1225	0.0000	0.0000
JHS9	134	6700	31	13	1174	0.0000	0.0000
Mean	**112**	**5100**	**31**	**14**	**1145**	**0.0001**	**0.0000**
s.d.	**23**	**1600**	**6**	**5**	**87**	**0.0001**	**0.0000**
Hillslopes in other soil types							
JHS1	120	3600	55	45	1167	0.0014	0.0000
JHS2	67	1100	55	38	1165	0.0009	0.0000
JHS3	249	11700	20	13	947	0.0001	0.0000
JHS5	82	3000	33	9	1133	0.0000	0.0000
JHS8	96	4200	50	27	1206	0.0000	0.0000
JHS10	84	1300	30	15	979	0.0668	0.0000
JHS11	67	1200	25	20	962	0.0045	0.0000
Mean	**109**	**3700**	**38**	**24**	**1080**	**0.0105**	**0.0000**
s.d.	**62**	**3600**	**14**	**13**	**108**	**0.0249**	**0.0000**

Appendix B. Area, elevation, and sediment production rates for hillslopes in the Providence Creek watersheds for WY2004 through WY2009. "NA" indicates that the fence did not collect valid data for that water year or was not yet constructed. "**" indicates missing data for that water year.

Hillslope	**Area (m^2)**	**Fence elevation (m)**	**Sediment production rate ($kg\ m^{-2}\ yr^{-1}$)**					
			WY2004	**WY2005**	**WY2006**	**WY2007**	**WY2008**	**WY2009**
PH1	3973	1970	0.0000	0.0000	0.0127	0.0000	0.0001	0.0000
PH2	3922	1973	0.0000	0.0000	0.0178	0.0000	0.0000	0.0000
PH3	4109	1914	0.0000	0.0000	0.1142	0.0000	0.0013	0.0000
PH4	14738	1925	0.0000	0.0000	0.0251	0.0000	0.0000	0.0001
PH5	6078	1904	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PH6	7124	1916	0.0000	0.0006	0.0072	0.0000	0.0001	0.0000
PH7	12194	1942	0.0000	0.0000	0.0180	0.0000	**	0.0000
PH8	4201	1960	0.0000	0.0015	0.0919	0.0000	0.0030	0.0000
PH9	2986	1957	0.0000	0.0046	0.0523	0.0000	0.0005	0.0000
PH10	1814	1808	NA	0.0000	0.0230	0.0000	0.0008	**
PH11	1504	1833	NA	0.0000	0.0000	0.0000	0.0020	0.0000
Mean	**5700**	**1918**	**0.0000**	**0.0006**	**0.0329**	**0.0000**	**0.0008**	**0.0000**
s.d.	**4200**	**54**	**0.0000**	**0.0014**	**0.0378**	**0.0000**	**0.0010**	**0.0000**

Appendix C. Area, elevation, and sediment production rates for hillslopes in the Bull Creek watersheds for WY2004 through WY2009. "NA" indicates that the fence was not yet constructed or did not collect valid data for that water year. "**" indicates missing data.

Hillslope	**Area (m^2)**	**Fence elevation (m)**	**Sediment production rate (kg m^{-2} yr^{-1})**				
			WY2005	**WY2006**	**WY2007**	**WY2008**	**WY2009**
BH1	14892	2294	0.0023	0.0002	0.0000	0.0000	**
BH2	12606	2332	0.0029	0.0037	0.0001	0.0018	0.0025
BH4	26186	2252	0.0017	0.0003	0.0000	**	0.0000
BH5	22726	2361	0.0019	0.0022	0.0000	**	0.0000
BH6	18562	2414	0.0013	0.0008	0.0000	0.0000	0.0001
BH7	38445	2426	0.0002	0.0001	0.0000	0.0000	0.0000
BH8	12182	**	NA	0.0000	0.0000	**	**
BH9	18235	**	NA	0.0014	0.0000	**	0.0000
Mean	**20500**	**2347**	**0.0017**	**0.0011**	**0.0000**	**0.0005**	**0.0004**
s.d.	**8700**	**68**	**0.0009**	**0.0013**	**0.0000**	**0.0009**	**0.0010**

Appendix D. Characteristics and sediment production rates for native surface road segments in Holland soil and other soil types in José Basin for WY2008 and WY2009. “NA” indicates that the fence did not collect valid data for that water year, the fence was not yet constructed, or the segment was graded. “**” indicates missing data.

Segment	**Length (m)**	**Area (m^2)**	**Slope (%)**	**Fence elevation (m)**	**Sediment production rate ($kg\ m^{-2}\ yr^{-1}$)**	
Native surface road segments in Holland soil					**WY2008**	**WY2009**
JBT1	44	96	9	986	3.8	NA
JBT14	43	91	10	1018	7.9	NA
JNH5	36	89	12	1181	0.1	0.0
JNH7	32	96	2	1083	0.2	0.0
JNH8	30	59	14	1014	1.7	0.1
JNH10	37	99	10	1124	0.2	0.1
JNH12	50	125	10	1141	0.1	0.4
JNH13	60	168	8	1137	1.5	0.1
JNH3	40	99	16	1215	NA	4.9
JNH6	29	75	10	1102	NA	7.4
JNH9	37	99	15	1025	NA	2.1
JNH11	30	90	12	1176	NA	0.4
JNH14	71	200	10	1137	NA	3.6
JPS11	40	120	10	1014	NA	5.2
JPS12	36	72	6	1134	NA	0.0
JPS14	53	164	12	1093	NA	2.9
JPS15	31	84	5	1129	NA	0.2
JPS18	70	168	9	1114	NA	0.1
JPS19	28	70	10	1105	NA	0.2
JPS21	28	62	12	1087	NA	0.3
Mean	**42**	**108**	**10**	**1109**	**1.9**	**1.6**
s.d.	**13**	**38**	**3**	**65**	**2.7**	**2.3**
Native surface road segments in other soil types						
JNO4	56	151	4	1011	0.1	0.1
JNO6	31	83	5	982	0.0	0.1
JNO8	37	100	6	958	0.1	0.0
JNO9	32	102	11	920	0.6	4.2
JNU1	28	65	10	1102	NA	1.7
JNO1	48	115	4	**	NA	0.1
JNO3	35	76	11	1015	NA	12.9
JNO5	50	156	14	960	NA	1.3
JNO7	35	94	11	970	NA	8.7
JPS1	45	167	10	913	NA	3.0
JPS3	80	208	8	1034	NA	0.1
JPS4	51	153	3	968	NA	1.6
JPS5	88	246	10	954	NA	0.6
Mean	**45**	**127**	**8**	**979**	**0.2**	**2.6**
s.d.	**17**	**48**	**3**	**47**	**0.3**	**3.9**

Appendix E. Characteristics and sediment production rates for native, gravel, and mixed surface road segments as well as ditches adjacent to paved roads in the Providence Creek watersheds for WY2004 through WY2009. "NA" indicates that the fence was not yet constructed or was removed for that water year.

Segment	**Length (m)**	**Area (m^2)**	**Slope (%)**	**Elevation (m)**	**Sediment production rate (kg m^{-2} yr^{-1})**					
					WY2004	**WY2005**	**WY2006**	**WY2007**	**WY2008**	**WY2009**
Native surface road segments										
PN1	35.0	95	6	1859	0.00	0.00	0.19	NA	NA	NA
PN2	52.6	140	9	1846	0.52	1.90	3.99	NA	NA	NA
PN3	23.9	69	4	1837	0.08	0.10	1.24	NA	NA	NA
PN4	70.3	232	4	1865	0.12	0.93	0.89	NA	NA	NA
PN5	139.3	514	7	1869	0.97	1.75	2.22	NA	NA	NA
PN6	31.1	87	12	1961	0.17	0.12	0.89	0.00	0.21	0.24
PN7	54.9	179	7	1964	0.11	0.51	2.69	NA	NA	NA
PN8	46.8	150	13	1747	1.07	4.24	6.17	0.22	0.04	0.29
PN9	40.7	148	7	1770	0.04	0.00	0.32	0.00	0.01	0.01
PN10	49.3	164	9	1844	0.15	0.03	0.35	0.00	0.02	0.23
PN11	31.7	94	13	1878	0.11	0.19	0.69	0.00	0.08	0.06
PN12	36.3	98	11	1838	NA	0.75	3.42	NA	NA	NA
PN13	68.0	218	7	1952	NA	0.24	0.51	0.01	0.37	0.03
Mean	**52**	**168**	**8**	**1864**	**0.30**	**0.83**	**1.81**	**0.04**	**0.12**	**0.14**
s.d.	**30**	**115**	**3**	**66**	**0.38**	**1.21**	**1.81**	**0.09**	**0.14**	**0.12**
Gravel surface road segments										
PG1	54.3	174	11	1965	0.14	0.30	1.02	0.02	0.02	0.21
PG2	26.0	73	19	1964	0.07	0.18	0.65	0.02	0.28	0.42
PG3	71.4	255	5	1748	0.00	0.04	0.16	0.23	0.00	0.01
PG4	67.3	244	3	1761	0.01	0.01	0.07	0.01	0.00	0.02
PG5	21.5	80	14	1766	0.03	0.12	0.87	0.00	0.03	0.09
PG6	67.1	239	13	1838	0.03	0.12	0.09	0.00	0.05	0.09
PG7	39.9	134	14	1871	0.02	0.20	0.74	0.00	0.02	0.19
Mean	**50**	**171**	**11**	**1845**	**0.04**	**0.14**	**0.52**	**0.04**	**0.06**	**0.15**
s.d.	**21**	**78**	**6**	**93**	**0.05**	**0.10**	**0.40**	**0.09**	**0.10**	**0.14**
Mixed surface road segments										
PM1	90.5	434	9	1822	0.19	0.79	2.63	0.07	0.58	0.16
PM3	150.7	652	9	1738	0.00	0.00	0.01	0.00	0.02	0.00
PM4	64.3	312	10	1760	0.02	0.21	0.37	0.00	0.18	0.01
PM5	75.6	288	12	1841	0.34	0.43	1.48	0.00	0.44	0.36
Mean	**95**	**422**	**10**	**1790**	**0.14**	**0.36**	**1.12**	**0.02**	**0.30**	**0.13**
s.d.	**38**	**167**	**1**	**49**	**0.16**	**0.34**	**1.19**	**0.03**	**0.26**	**0.17**
Ditches adjacent to paved roads										
PDi1	80.8	372	6	1941	0.000	0.014	0.018	0.000	0.011	0.004
PDi2	178.6	925	9	1948	0.000	0.000	0.000	0.000	0.000	0.000
PDi3	36.8	162	4	1910	0.000	0.000	0.000	0.000	0.000	0.000
PDi4	116.8	594	10	1891	0.000	0.014	0.064	0.000	0.001	0.002
PDi5	45.9	237	4	1894	0.000	0.000	0.000	0.000	0.017	0.004
PDi6	57.9	311	11	1758	0.010	0.020	0.581	0.000	0.046	0.031
PDi7	110.3	467	7	1822	0.000	0.000	0.000	0.000	0.000	0.001
Mean	**90**	**438**	**7**	**1880**	**0.001**	**0.007**	**0.095**	**0.000**	**0.011**	**0.006**
s.d.	**50**	**258**	**3**	**68**	**0.003**	**0.008**	**0.216**	**0.000**	**0.017**	**0.011**

Appendix F. Characteristics and sediment production rates for native surface road segments in the Bull Creek watersheds for WY2005 through WY2009.

Segment	**Length (m)**	**Area (m^2)**	**Slope (%)**	**Fence elevation (m)**	**Sediment production rate (kg m^{-2} yr^{-1})**				
					WY2005	**WY2006**	**WY2007**	**WY2008**	**WY2009**
BN1	33.9	88	13	2237	0.33	0.09	0.00	0.09	0.39
BN2	58.5	152	10	2245	0.28	0.11	0.00	0.04	0.68
BN3	54.2	201	5	2251	0.11	0.18	0.00	0.01	0.06
BN4	112.8	384	8	2248	0.56	0.56	0.00	0.03	0.24
BN5	76.5	252	10	2285	0.17	0.02	0.00	0.00	0.00
BN6	47.5	176	7	2374	0.03	0.00	0.00	0.00	0.03
BN7	36.6	149	8	2403	0.17	0.08	0.00	0.00	0.05
BN8	67.8	251	12	2247	0.30	0.04	0.00	0.20	0.62
BN9	29.4	92	4	2340	0.00	0.00	0.00	0.00	0.00
Mean	**57.5**	**194**	**9**	**2292**	**0.22**	**0.12**	**0.00**	**0.04**	**0.23**
s.d.	**26.0**	**92**	**3**	**64**	**0.17**	**0.18**	**0.00**	**0.07**	**0.27**

Appendix G. Characteristics and sediment production rates for gravel surface segments in José Basin for WY2008 and WY2009. “NA” indicates that the fence did not collect valid sediment production data for that year.

Segment ID	**Length (m)**	**Area (m^2)**	**Slope (%)**	**Fence elevation (m)**	**Sediment production rate (kg m^{-2} yr^{-1})**	
					WY2008	**WY2009**
JGH3	37	89	12	1106	3.4	1.1
JGH4	22	57	14	1080	3.5	1.4
JGH5	26	66	10	1071	6.6	3.4
JGH6	55	137	9	1115	3.3	0.1
JGH10	39	119	12	1219	1.4	0.0
JGH7	80	192	17	1071	NA	0.3
JGH8	60	173	11	1115	NA	0.3
JGH9	45	112	16	1164	NA	0.1
JGH11	29	68	15	1199	NA	0.6
JGH12	49	114	20	1134	NA	0.3
JGH13	25	55	19	1108	NA	0.1
Mean	**42**	**107**	**14**	**1126**	**3.6**	**0.7**
s.d.	**18**	**46**	**4**	**50**	**1.9**	**1.0**

Appendix H. Mean segment characteristics and waterbar data for six different road sections in José Basin prior to, immediately after, and one water year following grading.

	Prior to grading						**Immediately after grading**				**One year after grading**					
	Segment length				**Waterbars**		**Segment length**				**Segment length**				**Waterbars**	
Road	**n**	**Total**	**Mean**	**s.d.**	**n**	**% failed**	**n**	**Total**	**Mean**	**s.d.**	**n**	**Total**	**Mean**	**s.d.**	**Total**	**% failed**
9S61	71	3657	52	31	72	33	99	3670	37	20	83	3646	44	25	74	19
9S307	13	1864	143	302	17	82	44	1858	42	29	38	1841	45	38	10	50
9S304	21	1216	58	33	0	0	24	1239	52	33	23	1294	56	37	3	33
9S304A	4	225	56	37	6	83	6	220	37	14	9	222	25	10	32	25
9S61B	4	253	63	10	3	33	6	201	34	13	5	235	47	27	4	0
9S307A	11	860	78	71	11	64	18	847	47	37	14	840	60	57	5	0
Total	**124**	**8075**	**65**	**104**	**109**	**47**	**197**	**8035**	**41**	**26**	**172**	**8078**	**47**	**34**	**128**	**22**

Appendix I. Characteristics and sediment production rates for road segments one and two years after grading in José Basin. * indicates that the production data are from WY2008, while all of the other data are from WY2009.

Fence	Length (m)	Area (m^2)	Slope (%)	Fence elevation (m)	Sediment production rate (kg m^{-2} yr^{-1})
One water year after grading					
JBT8*	32	70	6	1013	6.1
JBT9*	23	51	5	1007	12.8
JBT10*	24	60	8	988	13.0
JBT1	44	96	3	980	0.9
JBT2	46	150	6	982	6.8
JBT3	47	107	4	1002	4.4
JBT4	32	83	7	1036	9.9
JBT5	39	113	9	1034	5.5
JBT6	60	145	3	979	0.5
JBT7	41	119	3	969	7.0
JBT11	83	200	4	993	12.4
JBT12	56	118	7	1018	3.7
JBT13	37	82	5	1019	3.2
JBT14	43	91	2	1032	3.7
JBT17	25	69	14	1004	12.5
JBT18	49	147	60	998	9.4
JBT19	30	76	15	1009	20.4
JBT20	23	64	20	1022	3.1
JBT21	58	151	13	1022	7.2
JNH4	41	90	9	1254	4.1
JNU1	28	65	1	1134	0.2
JNU2	29	67	3	1144	1.7
JPS16	45	153	2	1112	0.7
JPS17	85	204	5	1101	0.6
JPS20	16	43	8	1105	0.8
JPS22	32	90	3	1155	3.0
JPS23	29	78	5	1191	1.7
Mean	**41**	**103**	**9**	**1048**	**5.7**
s.d.	**17**	**43**	**11**	**74**	**5.1**
Two water years after grading					
JBT8	32	70	17	1156	2.4
JBT9	23	51	18	918	5.1
JBT10	24	60	14	847	8.2
Mean	**26**	**60**	**16**	**974**	**5.3**
s.d.	**5**	**10**	**2**	**162**	**2.9**