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WATER RESOURCE ISSUES AND SOLUTIONS FOR FOREST ROADS IN CALIFORNIA

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ABSTRACT

Unpaved forest roads are recognized as being the primary source of anthropogenic sediment that is delivered to stream channels in managed forested watersheds in the western United States. Research studies, sediment budgets, and agency monitoring projects in California have shown that road-stream crossings and road segments that drain to crossings are high-risk sites for sediment input. In particular, older "legacy" roads and crossings that pre-date current forest practice rules can be sources of chronic and episodic sediment delivery. Because many California streams provide habitat for listed anadromous fish species, there has been increased emphasis on reducing road-related sediment production. Numerous efforts are made by resource agencies, landowners, and watershed groups to address road-related sedimentation. Most owners of large forest parcels have road management plans for inventorying and prioritizing high-risk road sites for remedial treatments or decommissioning. State and federal grant and cost-sharing programs are used extensively to support road improvement projects. A recent review of state-funded road decommissioning work showed that accepted protocols are generally effective for preventing erosion and sediment delivery, but that they are not uniformly implemented at road-stream crossings. Training workshops and guidebooks are employed to improve stakeholder knowledge regarding proper design and installation of crossing structures and treatment of roads to reduce sediment delivery.

Key words: sediment delivery, forest roads, erosion, California

INTRODUCTION

Unpaved roads are a major anthropogenic cause of sedimentation in many forested watersheds of the western United States (Megahan and Kidd 1972, Reid and Dunne 1984, Luce and Black 1999, MacDonald et al. 2004, Sugden and Woods 2007). Road-related sediment sources include surface erosion, gullying and mass wasting (Reid and Dunne 1984, Wemple et al. 2001). Sediment may be delivered to streams either episodically when roads or road-stream crossings catastrophically fail, or chronically due to incremental surface erosion. Excessive sedimentation associated with roads is of concern because of potential impacts on stream habitat and water quality (Cederholm et al. 1981, Murphy 1995, Waters 1995, Spence et al. 1996).

Forest roads provide access for timber operations and fire suppression. In California alone, it is estimated that there are at least 60,000 kilometers of unpaved road on approximately 22,000 square kilometers of private commercial timberland zoned for timber production (CDF 2003). Public lands, such as National Forests, have thousands of kilometers of additional unpaved roads. Many of these roads were built decades ago to very low design standards, often in environmentally sensitive locations such as on unstable slopes and near streams. A significant number of the older roads are part of the current road network, while others were neglected and abandoned with no consideration of ongoing erosional impacts. These "legacy" roads are particularly susceptible to catastrophic failure during high magnitude, low frequency storm events, such as the one in 1997 that caused extensive flooding throughout a large part of northern California (Furniss et al. 1998, Madej 2001).

In this paper, we review results from field, modeling and monitoring studies of forest road effects on erosion and sediment delivery in California. We then describe the regulatory and voluntary efforts that are being used by agencies and landowners to reduce adverse impacts of forest roads. Although many steps are being taken to address these problems, there are still lingering issues. New regulatory, monitoring and educational initiatives are briefly summarized.

LITERATURE REVIEW OF THE EFFECTS OF FOREST ROADS ON EROSION AND SEDIMENTATION IN CALIFORNIA

Regional variations in climate, geology, topography, and road construction practices drive the interactions between geomorphic processes and road networks (Montgomery 1999, Jones et al. 2000, Wemple et al. 2001). Consequently, road study methods and results have varied widely as a function of California's diverse geomorphology (Harden 1997, CGS 2002).

In response to this variability, we stratify studies into the following geomorphic regions: the northern Coast Range (i.e., North Coast), the Cascade Range, the Sierra Nevada, and the Klamath Mountains. The North Coast is dominated by the landslide-topography of the highly erodible Franciscan Complex (Jennings 2000, Harden 1997) and has some of the highest unit area peak runoff rates in the United States (O'Connor and Costa 2004). The Cascade Range is located in northeastern California and terminates at Lassen Peak. It is composed of relatively resistant volcanic rocks, gently sloping tablelands, and low overall stream density (Harden 1997, Benda et al. 2003). The Sierra Nevada's western slope is gently sloping with deeply incised river canyons, while the eastern escarpment has steeper slopes. Its geology consists primarily of granitic, metamorphic and volcanic rocks with varying erosion potentials. The Klamath province is located between the Coast and Cascade Ranges in northern California and is geologically similar to the Sierra Nevada, but with highly dissected topography and a climatic regime similar to the North Coast.

To compare data and to provide a watershed context, we have converted erosion rates into consistent units that reflect the annual mass of road erosion in a watershed (i.e., Mg km^{-2} yr^{-1}). The originally reported erosion rates are shown in Table 1. We assign a bulk density of 1.6 g cm^{-3} to convert volume estimates to mass, as has been done elsewhere in California (Best et al. 1995, Pitlick 1995, Coe 2006). Rates are normalized by watershed area by dividing the mass of erosion by the study area, or by multiplying mass per unit length of road (i.e., Mg km^{-1}) by the total length of road in the study area, or by the average road density of the study area. While we recognize that some erosion processes are episodic in nature, rates are normalized by number of years in the study period for comparison. These normalized erosion rates are to provide readers the ability to evaluate the relative differences in erosion rates between different road erosion processes (i.e., mass wasting vs. gully erosion vs. surface erosion) and different geomorphic regions.

Research Studies

Most of the road erosion studies in California have been conducted in the Coast Ranges. This includes a suite of studies that documented the effects of logging on sedimentation in the Redwood Creek watershed in Humboldt County. Most of these studies evaluated the integrated impact of past logging practices from the 1950's to 1970's and did not explicitly evaluate the impacts of logging after the passage of the California Forest Practice Act of 1973. These studies found that inadequately designed road-stream crossings were responsible for stream diversions and very high rates of gully erosion in tributaries to Redwood Creek at Redwood National Park (Hagans et al. 1986, Weaver et al. 1987, Hagans and Weaver 1987, Weaver et al. 1995, Best et al. 1995). Episodic gully erosion from diverted road-stream crossings in five Redwood Creek tributaries produced 8600 Mg km^{-2} over 33 years, or an average of 260 Mg km^{-2} yr^{-1} (Hagans et al. 1986). Sediment production from discrete road induced landslides averaged from 155-176 Mg km^{-2} yr^{-1} over approximately a 25 to 28 year time span (i.e., mid-1950's to early-1980's) (Best et al. 1995, Pitlick 1995). Surface erosion from roads and skid trails was less important, accounting for only 4 percent of measured sediment in the lower Redwood Creek basin or an average yearly input of 34 Mg km^{-2} yr^{-1} (Weaver et al. 1987, Hagans et al. 1986, Hagans and Weaver 1987). Road related erosion comprised more than 30 percent of the total sediment budget over a 25-year time span, or 356 Mg km^{-2} yr^{-1}, for the 10.8 km^2 Garret Creek watershed (Best et al. 1995).

Rice (1999) assessed road erosion on private lands in a portion of the Redwood Creek basin and found that erosion averaged 43 Mg km^{-2} yr^{-1} over a 17-year time span from 1980 to 1997. This rate was 12 percent of the value reported for the Garret Creek watershed (Best et al. 1995). Rice (1999) cautioned about direct comparisons of studies with different objectives and methods, but concluded that the lower rates of erosion were due to improved road requirements mandated by the Forest Practice Rules.

In the Caspar Creek watershed located in Mendocino County, erosion and sediment yield associated with timber harvesting and roads have been studied since 1962 (Lewis et al. 2001). As in Redwood Creek, high levels of erosion have been attributed to roads that were constructed prior to 1973 (Rice et al. 2004). Approximately 70 percent of landslides that occurred after logging in the South Fork of Caspar Creek were associated with roads and landings (Cafferata and Spittler 1998). Over a four-year period, erosion due to roads in the South Fork of Caspar Creek was estimated at 130 Mg km^{-2} yr^{-1} (Krammes and Burns 1973). In the North Fork, where timber operations were conducted under modern forest practice rules, road-related erosion was less than half that measured in the South Fork, and the erosion was rarely delivered to the channel network due to road location (Rice et al. 2004). In Caspar Creek and three nearby watersheds, landslides in clearcut units that delivered sediment to stream channels were mostly associated with old roads that were constructed decades ago (Bawcom 2003).

The findings of studies at Redwood and Caspar Creeks are corroborated by other studies in the North Coast region. McCashion and Rice (1983) evaluated 553 kilometers of logging roads in the Six Rivers National Forest of Humboldt County and found that the road network produced 60 percent of the management-related erosion. Approximately 95 percent of the road-related erosion was from mass wasting. A mass wasting study on non-federal timberlands encompassing the entire North Coast and North Interior parts of the state found that 76 percent of management-related erosion was related to roads and landings (Durgin et al. 1989; Lewis and Rice 1989, Rice and Lewis 1991). Weaver and Hagans (1999) documented that road-related sediment delivery over a 50 year period in three Humboldt County watersheds ranged from 37 to 185 Mg km^{-2} yr^{-1}, with the majority of sediment coming from stream crossing diversions and road fill failures.

There has been less research on forest road erosion in the Klamath, Sierra Nevada, and Cascade regions of California. Road impacts in areas with soils derived from highly erodible decomposed granitic parent material have been studied in some locations. In the Scott River basin of the Klamath Mountains, Sommarstrom et al. (1990) found that road cuts in decomposed granitic soils produced 64 percent of road-related erosion. Erosion rates from roads (33 kg m^{-2} yr^{-1}) were comparable to those reported for other California watersheds with decomposed granitic soils. Their study represented the condition of roads pre-1990, before most road improvement efforts began on private and public lands in this area.

There have been recent studies of road surface erosion in the central and southern Sierra Nevada, where mass wasting is infrequent (Rice and Lewis, 1991, MacDonald et al. 2004). Coe (2006) documented sediment production and delivery in the central Sierra Nevada on both National Forest and private forest lands. Data were collected from sites with soils derived from weathered grandodiorite, andesitic lahar deposits, and granitic glacial deposits. There was a 16-fold difference in median sediment production rates between rocked and un-rocked road segments, and roads that had been recently graded produced more than twice the sediment per unit area as un-graded roads. The highest rates of erosion came from road segments with unusually high rates of subsurface stormflow interception by road cutslopes. Spatially, stream crossings were the main linkage for sediment delivery to the channel network, although road-induced gullies delivered almost as much sediment to the channel network as chronic surface erosion. Assuming a road density of 3.1 km km^{-2} (i.e., 5 mi mi^{-2}), Coe (2006) estimated that approximately 6 Mg km^{-2} yr^{-1} of road sediment would be delivered to the channel network. Sediment delivery problems were mostly related to older roads. Newer roads or roads upgraded to current Forest Service and State Forest Practice Rule standards performed better than older roads.

In the southern Sierra Nevada, Korte and MacDonald (2007) measured road and hillslope erosion over three winters during the calibration period of the Kings River Experimental Watershed Study (KREW) (Hunsaker and Eagan 2003). The dominant lithology in the KREW study area is granite. Their results are consistent with the results from earlier work in the central Sierra Nevada (MacDonald et al. 2004, Coe 2006). High variability in sediment production rates was found between years, between different types of road surfaces, and between individual road plots. Native and mixed surface roads produced approximately three times the sediment as gravel surfaced roads. The estimated sediment delivery from roads was compared to the measured sediment yields in three of the lower-elevation watersheds, and in two of these watersheds forest roads were estimated to contribute less than 10 percent of the measured sediment yield. In the third basin roads were estimated to contribute 25-50 percent of the total sediment yield, and nearly all of the road-related sediment came from a single mixed surface road that crossed the stream a short distance above the weir pond (A. Korte, Colorado State University, Fort Collins, CO, personal communication).

Sediment Budgets and Road-Related Sediment

Numerous sediment budgets have been developed for watersheds in the Coast Ranges, most of which have relied on aerial photograph analysis of landslide and surface erosion features, GIS digital terrain models, and limited field investigation. Rapid sediment budgets can produce estimates within a factor of two of actual sediment yield (Reid and Dunne 1996). Most of this work has been done as part of Total Maximum Daily Load (TMDL) watershed assessments. TMDLs are pollution control plans produced for watersheds listed as impaired by U.S. EPA under the Federal Clean Water Act. In general, these sediment budgets reveal that road surface erosion and road-related landslides are the dominant sources of sediment from current land management activities. Erosion from timber harvesting units is usually less significant. In a review of TMDL documents for nine North Coast watersheds, Kramer et al. (2001) reported that, on average, roads and skid trails contributed approximately two-thirds of all management-related sediment loading. This concurs with our analysis of 19 sediment budgets (16 produced for Coast Range basins), which shows that road-related sediment is responsible for approximately two-thirds of management-related sediment, or roughly one-third of total sediment production (Figure 1). Total natural and management-related sediment loads were estimated to be approximately equal. Kramer et al. (2001) were not able to discern to what degree older roads or roads constructed under current Forest Practice Rules were responsible for sediment production.

Forest roads do not dominate management-related sediment production in all watersheds where sediment budgets have been estimated. Roads were relatively smaller sources of total estimated sediment yield in the highly unstable Van Duzen watershed (U.S. EPA 1999) and in the Scott River basin, where stream bank failures were estimated to produce a significant proportion of total sediment (NCRWQCB 2005) (Figure 2).[1] In the Bear Creek and Jordan Creek watersheds of Humboldt County, PWA (1998a, 1999) estimated that roads produced only 8 percent and 21 percent of total sediment delivery, respectively. Hillslope and streamside landslide erosion are the dominant sediment sources in these two small, highly unstable basins.

As with road erosion studies, there have been few sediment budgets developed for the Klamath Mountains and the Sierra-Cascade region. Sommarstrom et al. (1990) produced a sediment budget for granitic tributaries of the Scott River watershed. They estimated that roads contributed 82 percent of the management-related sediment in these drainages. Of the total erosion, road cuts represented 40 percent of the soil loss, road fill 21 percent, and road surfaces 2 percent. Other sources included streambanks (23 percent), skid trails (13 percent), and landslides (<1 percent). Benda et al. (2003) produced a sediment budget for the Judd Creek watershed, a small tributary to Antelope Creek, which drains into the Sacramento River below Redding in the southern Cascade Range. No landslides were observed in this basin, where the average hillslope gradient is only 15 percent (Benda et al. 2003). Road-related erosion was estimated to produce only 3.5 percent of total estimated sediment yield, or an annual input of 9.4 Mg km^{-2} yr^{-1}, while post-fire erosion (68 percent) and bank erosion/soil creep (28 percent) dominated long-term sediment production. Considering just management-related erosion, road surface erosion and harvest unit erosion were estimated to produce 87 percent and 13 percent of the total, respectively. Benda et al. (2003) suggested upgrading or decommissioning logging roads within 60 meters of stream channels that have a high probability of sediment delivery to reduce forestry impacts on water quality.

Reid and Dunne (1996) produced a sediment budget for the higher elevation area of the KREW project in the southern Sierra. They estimated that bank erosion was causing half of current sediment delivery. Road surface erosion was the only disturbance category listed and was estimated to contribute less than one-quarter of the total sediment yield, or approximately 3 Mg km^{-2} yr^{-1}. Long-term post-fire erosion was not estimated. Euphrat (1992) created a sediment budget for the upper Middle Fork of the Mokelumne River in the central Sierra Nevada, which is heavily used for commercial timber harvesting. He estimated that road surfaces produced approximately 40 percent of the annual erosion. Nolan and Hill (1991) developed sediment budgets for four Lake Tahoe tributaries on the east slope of the Sierra Nevada and found that nearly all mobilized sediment was derived from stream channels (either stream banks or streambed). Hillslope erosion was a minor component of these sediment budgets, ranging from less than 5 percent to 11 percent.

Agency Monitoring Programs Related to Road Erosion

Monitoring programs conducted by state and federal (U.S. Forest Service) agencies have documented the frequency and causes of road-related erosion problems on private and public timberlands in California. This monitoring has been conducted in conjunction with evaluation of state Forest Practice Rule and Forest Service Best Management Practice (BMP) effectiveness. The earliest monitoring project was a qualitative assessment of 100 state-issued Timber Harvesting Plans (THPs) conducted in 1986 by a team of four resource professionals on non-federal timberlands. The team concluded that the Forest Practice Rules were generally effective when implemented on terrain that was not overly sensitive (i.e., erodible soils, high mass wasting potential), and that poor rule implementation was the most common cause of water quality impacts. Poor road location, construction, drainage and/or abandonment were noted as common reasons for significant adverse impacts (CSWRCB 1987).

[1] The Scott River TMDL sediment budget listed roads as one category, but they were a large part of an additional category denoted as "Effects of Multiple Interacting Human Activities" (EMIHA), since road runoff affecting streambank stability was included. Therefore, it is difficult to determine the total percentage of road-related sediment for this basin from the TMDL document (S. Sommarstrom, Etna, CA, personal communication).

The qualitative assessment completed in 1986 was not considered sufficient evidence for certifying the state Forest Practice Rules as adequate best management practices. Consequently, two state-sponsored THP monitoring programs were conducted from 1996 through 2004. The Hillslope Monitoring Program (HMP) analyzed data collected by private contractors from 1996 through 2001 on 300 randomly selected THPs and Non-industrial Timber Management Plans (NTMPs) located throughout the state on non-federal timberlands (Cafferata and Munn 2002, Ice et al. 2004). The objective of the program was to evaluate the implementation and effectiveness of the California Forest Practice Rules in protecting water quality. On-site data were collected from randomly located 305 meter (1000 foot) road segments and at road-stream crossings, along with other high risk locations (i.e., skid trails, landings, etc.). The HMP found that the implementation of rules governing roads averaged 93 percent and that the required practices appeared to have been effective in preventing erosion when they were properly implemented. For this study, road erosion features were almost always associated with improperly implemented Forest Practice Rules. Overall, 5.5 percent of the road drainage structures were inadequately designed, constructed, or maintained on the 167 kilometers of road segments monitored, and approximately 15 percent of the 1,132 inventoried road erosion features (i.e., rills, gullies, mass failures, cutslope/fillslope sloughing) delivered sediment to stream channels.

In a similar study, California Department of Forestry and Fire Protection Forest Practice Inspectors collected onsite monitoring data from 2001 through 2004 as part of the Modified Completion Report (MCR) monitoring program (Brandow et al. 2006). A random draw of 12.5 percent of all completed THPs was evaluated (281 THPs), and high risk and highly sensitive parts of each plan (roads, crossings, and stream buffers) were randomly sampled and evaluated. Nearly all the identified road rule implementation departures were related to drainage (e.g., water-break spacing). Five percent of inventoried road-related features had improper implementation of rule requirements, and approximately 8 percent of road erosion features delivered sediment to stream channels, nearly always when road rules were improperly implemented. Road-stream crossing effectiveness ratings were generally similar to HMP results and showed that diversion potential, culvert plugging, and road drainage structure function near crossings were common problem areas. Approximately 20 percent of the stream crossings in both the MCR and HMP studies had significant implementation and/or effectiveness problems.

On federal lands in California, the U.S. Forest Service collected data from 1992 through 2002 on over 3,100 randomly located sites to evaluate the implementation and effectiveness of its water quality BMPs (USFS 2004). The BMP Evaluation Program used 29 different onsite monitoring protocols to evaluate BMP implementation and effectiveness, with the majority related to timber and engineering practices. Results showed that while some improvements to current practices were necessary, the program performed reasonably well in protecting water quality on National Forest lands (approximately 8 million hectares or one-fifth of the state). BMP implementation and effectiveness were relatively high for most activities (including timber and engineering) and impacts on water quality were relatively rare, particularly in recent years. Significant water quality impacts were typically caused by lack of or inadequate BMP implementation and mostly related to engineering practices (nearly 60 percent). Roads, and in particular stream crossings, created the greatest number of problems. Fifty-four percent of the sites where elevated water quality impacts were observed were associated with roads.

Summary of Literature Review

Research studies, sediment budgets and monitoring throughout California's forestlands have all identified road-related erosion as a prominent factor affecting sediment yields in watersheds managed for timber production. In the relatively unstable North Coast region, road-related mass wasting has been well-documented, but there has been less emphasis on road surface erosion. In the Sierra-Cascade region, hillslope instability is less common (Durgin et al. 1989), and the few studies that exist focus on road surface erosion. Causal mechanisms for road-related erosion have been identified through state and federal monitoring programs. Sediment budgets reveal that roads often produce at least two-thirds of management-related erosion in forested watersheds. Older "legacy" roads that pre-date current state Forest Practice Rules and U.S. Forest Service BMPs are commonly identified as a major source of sediment. Usually a small proportion of the total road system produces most of the sediment and there are certain site factors that predispose a road segment or road-stream crossing to erosion. In particular, native surface road segments located within 60 meters of streams that are connected to the channel by inboard ditches are particularly high-risk sites for fine sediment delivery.

To place road erosion rates into proper perspective it is important to compare rates of road-induced erosion to long-term background erosion rates. In recent years, background erosion rates have been derived over millennial time scales using cosmogenic radionuclide dating (Riebe et al. 2000, Kirchner et al. 2001, Ferrier et al. 2005). When compared to millennial averaged sediment production rates derived from cosmogenic radionuclide (CRN) dating (Riebe et al. 2001, Ferrier et al. 2005), road erosion rates are approximately equal to long-term rates in the North Coast and are an order of magnitude lower in the Sierra Nevada (Figure 3). Given that road erosion rates and background erosion rates for the North Coast are almost equal in magnitude, we conclude that roads have increased the risk and size of catastrophic erosion events in the North Coast region. While data are limited from the Sierra Nevada, we hypothesize that long-term erosion in the Sierra Nevada is dominated by infrequent, catastrophic disturbance and is similar to the erosional regime reported for the Idaho Batholith, where incremental erosion occurs most of the time but is a small fraction of long-term sediment yield (Kirchner et al. 2001). The disparity between road erosion rates and long-term background erosion rates in the Sierra Nevada (Figure 4) indicate that impacts from road erosion may be more an issue of timing rather than magnitude, as chronic erosion has the potential to disrupt aquatic ecosystems that are adapted to infrequent, catastrophic erosion (Kirchner et al. 2001).

APPROACHES FOR MITIGATING EFFECTS OF FOREST ROADS

Landowners and agencies address erosion and sedimentation caused by forest roads in California with both voluntary and regulatory approaches. The state Forest Practice Rules have been recently modified to address road erosion issues based on agency monitoring results and because of state and federal listings of anadromous fish species. One Regional Water Quality Control Board is requiring Erosion Control Plans for projects involving timber operations. Landowners have undertaken inventories to identify high-risk road segments and stream crossings for repair or removal. These inventories are commonly done in conjunction with the preparation of road management plans. Finally, there have been many road and stream crossing upgrading and decommissioning projects implemented using both private and public funds.

Regulatory Approaches

California's Forest Practice Rules contain extensive requirements designed to limit road erosion and sediment delivery associated with timber harvesting on non-federal timberlands (CDF 2007). To mitigate impacts from past poor road location and construction practices, the Forest Practice Rules require that existing road erosion sources must be repaired as part of an approved THP to lessen or avoid significant adverse water quality impacts. Numerous specific rules are enforced, such as the requirement that road-stream crossings be constructed and maintained in a manner that prevents diversion of streamflow down roads, which has been mandated since 1990. Rules added in 2000 require special road design and construction practices in watersheds with state or federally listed threatened and endangered fish species.[2] Among other things, these rules specify that roads should be out-sloped where feasible and drained with rolling dips or water-breaks, to reduce hydrologic connectivity and sediment delivery to streams. Additionally, to reduce the potential impacts of road-stream crossings, since 2000 the Forest Practice Rules have specified that all constructed or reconstructed permanent road-stream crossings must accommodate the estimated 100-year flow, including debris and sediment. To ensure that the Forest Practice Rules and additional THP requirements have been properly prescribed and implemented, California Department of Forestry and Fire Protection Forest Practice Inspectors conduct field inspections before, during and after harvesting.

In 2003, the Regional Water Quality Control Boards (RWQCBs) in California began requiring a permit for discharge of sediment from timber harvesting on non-federal timberlands. The North Coast Regional Water Quality Control Board's (NCRWQCB) permit program requires prevention/minimization of new sediment sources and mitigation of existing sediment sources through an Erosion Control Plan (ECP). The ECP outlines how a landowner will identify areas of sediment delivery, identify areas at risk of sediment delivery, and control sediment delivery associated with past and present land management activities (NCRWQCB 2001). The ECP requirement has forced landowners on the North Coast to make improvements on roads over and above those mandated by the Forest Practice Rules. In addition, the Central Valley Regional Water Quality Control Board (CVRWQCB) requires that landowners perform qualitative hillslope monitoring for most THPs, with an emphasis on checking road segments and stream crossings that pose a high risk to water quality (CVRWQCB 2007).

Voluntary Approaches—Road Inventory Work and Modeling

Road inventories and assessments are used to determine which roads on an ownership have the potential to deliver large amounts of sediment to streams, to establish priorities for road improvement (or upgrading) projects, and to develop road decommissioning schedules (Weaver and Hagans 1999, CDFG 2006). Although these inventories have been conducted on numerous California properties, industrial forest managers have taken particular interest and initiative in completing them to reduce potential restrictions on future operations. The main steps for road inventory work include: (1) identifying all permanent, seasonal, temporary, and historic or "legacy" roads, usually with aerial photographs, (2) conducting a field inventory to document erosion sources that can deliver sediment to the stream channel, (3) inputting the estimates of potential sediment delivery in a database and summarizing the data, and (4) developing a plan to remedy identified problem sites

[2] Ligon et al. (1999) made recommendations for changes in forestry regulations related to protection of salmonid habitat, including suggested changes for rules related to road construction/maintenance and stream crossings. Some of the recommendations were included in the Threatened or Impaired Watersheds Rule Package passed by the State Board of Forestry and Fire Protection in July 2000.

(CDFG 2006). Estimates of potential sediment delivery are calculated and categorized by source (i.e., number of cubic meters of sediment due to perched fill, inadequate crossing design, etc.) (CDFG 2006). All stream crossings are included along with a rating of their ability to pass a designated flood flow (e.g., 100-year recurrence interval flood), ability to allow fish passage (if applicable), diversion potential (should the crossing fail), mechanical damage or repair needs, etc.

Predictive models are sometimes used to identify roads with the highest potential for sediment delivery. These include the physically-based Disturbed WEPP:Road and the empirical SEDMODL/SEDMODL2. A field test of these models in the Oregon Coast Range found that SEDMODL2 produced erosion estimates much closer to measured sediment data than WEPP:Road, but neither model consistently ranked the sediment production rates from measured road segments (Amman 2005). For this reason, road erosion models are best used to estimate the relative magnitude of road erosion at the watershed scale (Raines et al. 2005). Models can also be used as conceptual tools that provide a sound basis for field data collection (Raines et al. 2005).

Through road inventory work, assisted by modeling efforts in some cases, landowners have developed databases with lists of road segments/sites rated as high, moderate, or low priority for improvement work. Options for improvement work include road decommissioning, upgrading, and no-action. Cost-effectiveness for treating individual sites and road segments is determined by dividing the cost of accessing and treating a site by the volume of sediment prevented from delivery to stream channels (Weaver and Hagans 1999). Treatment priorities are then established, with the road sites and road segments having the most cost-effective treatments implemented first. High priority treatment sites typically have at least 19 m^3 (25 yd^3) of sediment delivery potential to a stream channel, a high or moderate treatment rating, and a predicted cost-effectiveness of approximately \$7 to \$20/m^3 or less (PWA 1998b). The largest road sediment sources for the North Coast region are usually: (1) stream crossing fills, (2) fill slope failures, and (3) road surface erosion (W. Weaver, PWA, Arcata, personal communication). For the Sierra Nevada, where there is a much lower landslide frequency, road surface erosion and gully erosion are usually the largest sediment sources.

Road inventory and modeling work on both private and public landowners are often part of a more comprehensive road management plan (RMP). These are long-term plans for the ownership's transportation system and are often included as part of larger scale land management plans or landscape-level documents. RMPs usually include a section for scheduling/prioritization of sites requiring work based on completed or anticipated road inventory work. They also commonly have sections for specifying road design and construction standards, road use restrictions, and a road inspection/maintenance program.

Completed Road Improvement Work

The identification and treatment of problematic road sites and road segments has become big business on the North Coast of California. Millions of dollars of public and private money are expended yearly on upgrading or "decommissioning" (i.e., closing or removing) problem roads and stream crossings. Road improvement work is funded by a variety of sources, including state and federal funding for public ownerships, private funds for company timberlands, and grants provided by state and federal programs for non-federal timberland owners. State and federal grant and cost-sharing programs are used extensively to support road improvement projects.

Most publicly funded road improvement projects are catalogued in the California Habitat Restoration Project Database (CHRPD) maintained by the California Department of Fish and Game (DFG) and the Pacific Marine Fisheries Management Council. The CHRPD was queried to provide summary data on state funded road projects. Altogether, on all types of ownerships, nearly 1,600 kilometers of roads have been treated or are under contract to be treated utilizing funding provided by DFG. Forty percent of these road segments are or will be decommissioned and 60 percent upgraded. Approximately 4,000 road-stream crossings have been removed or replaced over the past 10 years in coastal California using state and federal grant funding (L. Williams, DFG, Sacramento, CA, personal communication).

Road improvement work has occurred on industrial timberland in California using a combination of private and public funding. The Pacific Lumber Company (PALCO) has "storm-proofed" (i.e., added surface rock, upgraded crossings, hydrologically disconnected) 845 kilometers of sub-standard road at a cost of \$22,000-25,000 per kilometer over the past seven years and has upgraded (i.e., improved crossings, hydrologically disconnected) an additional 438 kilometers of road (K. Sullivan, PALCO, personal communication). The company had also decommissioned 61 kilometers of road through 2004 (J. Barrett, PALCO, personal communication). All of this work has been done at company expense. Other major timber companies in California also have road upgrading and decommissioning programs. As of 2004, roughly 129 kilometers of road had been decommissioned on land owned by Green Diamond Resource Company (formerly Simpson), Hawthorne Timber Company and Mendocino Redwood Company, using matching funds from the DFG (W. Weaver, Pacific Watershed

Associates, personal communication). Mendocino Redwood Company alone has decommissioned in excess of 62 kilometers of road from 1998 through 2006 (K. Vodopals, Mendocino Redwood Company, personal communication). Campbell Timberland Management (CTM, managers for Hawthorne Timber Company lands) partners with cooperators such as Trout Unlimited to seek restoration grant funding through state and federal programs. These programs have facilitated road inventorying and road restoration projects at the planning watershed (1,200 to 4,000 ha) scale. Restoration grant projects are not linked to Timber Harvesting Plan permits, but rather occur as part of an ongoing environmental enhancement program. CTM prioritizes watershed restoration efforts based on two criteria: (1) maintenance or improvement in watersheds with the highest quality habitat and the most robust populations of listed anadromous fish, and (2) watersheds targeted by state or federal planning documents as key watersheds for recovery (P. Ribar, Campbell Timberland Management, personal communication).

In the Klamath Mountains, local watershed organizations have been active in bringing together stakeholders to complete watershed-scale forest road inventories and road improvement work (S. Farber, Timber Products Company, Yreka, personal communication). One notable success story has been the French Creek Watershed Advisory Group, which includes the U.S. Forest Service, Fruit Growers Supply Company, Timber Products Company, Roseburg Resources Company, and the Siskiyou County Road Department. In this watershed composed of decomposed granitic soils, over 61 kilometers of road was re-contoured and rocked, 6 kilometers of road were decommissioned, and many kilometers of road were closed to wet season use. Improvements in aquatic habitat conditions in French Creek have been documented with instream monitoring following the completion of the road improvement work (S. Sommarstrom, Etna, personal communication). An unknown but potentially substantial amount of road upgrading and decommissioning has been done at private expense on industrial timberland in the Sierra-Cascade region (Harris and Cafferata 2005).

Road upgrading and decommissioning is also occurring on public land. The U.S. Forest Service, National Park Service, Bureau of Land Management (BLM) and California State Parks have all been working to reduce sediment production from their road systems, primarily by decommissioning old logging roads. The Forest Service decommissioned 2,500 kilometers of road in California from 1994 through 2005 and reconstructed an additional 11,916 kilometers (J. TenPas, USFS, Vallejo, personal communication). Since 1978, 370 kilometers of former logging road, including 990 stream crossings, have been decommissioned in Redwood National Park (Harris and Cafferata 2005). The BLM decommissioning program has focused on lands in the Sinkyone Wilderness, the Mattole River watershed, the South Fork Eel River basin, and the Headwaters Forest Reserve, all of which are in Mendocino and Humboldt Counties. Since 1995, the BLM has decommissioned approximately 56 kilometers of former logging roads (D. Averill, Bureau of Land Management, personal communication).

In rural subdivisions in the Coast Ranges, at least 322 kilometers of road have been upgraded and 16 kilometers of road decommissioned using DFG funds (W. Weaver, PWA, personal communication). Also, the Five County Salmon Conservation Program, which covers Del Norte, Humboldt, Mendocino, Trinity and Siskiyou Counties, has led efforts to improve the quality of county-maintained road systems (M. Lancaster, Trinity County Planning Department, personal communication). This has included complete assessments of future sediment delivery, the development of prioritized plans for thousands of sediment reduction projects, and the identification and elimination of barriers to fish passage (Lancaster and Pérez 2001). Some coastal counties have increased their regulatory controls over rural road construction, primarily through the development and enforcement of grading ordinances.

Effectiveness of Current Road Improvement Approaches

Several assessment and monitoring projects have been undertaken to determine how effective road decommissioning and upgrading work has been in reducing road impacts. PWA (2005a) evaluated 82 kilometers of road decommissioning completed between 1998 and 2003 with funding from DFG in northwestern California, including 275 stream crossings and 111 landslides. The purpose of this assessment was to ascertain whether DFG's standard protocols for road decommissioning were successful in achieving their objectives. These procedures include complete removal of crossing fill material, excavation of unstable fill from the road prism and landings, and disconnecting road drainage from stream channels.

Overall, 57 percent of the crossing sites evaluated did not meet one or more of the accepted DFG decommissioning protocols. Crossings were found to account for 85 percent of the documented post-decommissioning sediment delivery. The average post-project sediment delivery at crossings was approximately 5 percent of the pre-treatment fill volume and the estimated average erosion for all 275 decommissioned crossings was approximately 26 m^3 following one to six over-wintering periods. The average delivery volume for stream crossings meeting DFG protocols was 18 m^3/site, while the average delivery volume for crossings that did not meet one or more of the DFG decommissioning standards was 32 m^3/site. PWA (2005a) concluded that erosion and sediment delivery from decommissioned stream crossings is unavoidable at all but the smallest crossings. The most common problem at decommissioned stream crossing sites was unexcavated fill. Sixty percent of sediment delivery at decommissioned stream crossings was due to natural or relatively unavoidable causes and 40 percent was attributed to operator or supervision problems. Approximately 70 percent of the avoidable operator-caused erosion was due to unexcavated fill left in the crossing. PWA (2005a) further concluded that: (1) the DFG decommissioning protocols for stream crossings are effective but are not being uniformly implemented at all sites, (2) the DFG decommissioning protocols for landslides are effective and are being followed, and (3) the DFG decommissioning protocols for road drainage are effective and are being employed correctly.

Short-term sediment impacts due to channel adjustments following crossing removal have been documented in several other smaller-scale northwest California studies (Klein 1987, Madej 2001, Klein 2003, PWA 2005b, and Keppeler et al. 2007). Post-project sediment delivery at stream crossings for these studies has ranged from approximately 12 m^3 to 50 m^3 (Figure 4). In general, these studies have shown that road treatments can reduce the long-term sediment production from decommissioned roads. Excavated crossings are the major short-term source of sediment input to stream channels following road decommissioning. Post-treatment sediment delivery from decommissioned crossings will likely be approximately 5 percent of pre-treatment sediment delivery potential, but can range up to roughly 20 percent. Most of the sediment input at excavated crossings can be expected to occur during the first few winters following treatment.

Only one study conducted to date has documented sediment delivery associated with stream crossing upgrade work. Harris et al. (in press) studied 30 crossings in small headwater streams located in northwestern California before and after new culverts were installed as part of THPs. They found that 11 sites showed no measurable erosion or sediment delivery. Five sites produced 3.8 m^3 or more of sediment, mainly due to channel incision. The maximum sediment production was approximately 7.6 m^3 at two sites, and average erosion for all sites was roughly 1.5 m^3 (Figure 4). In general, the extensive erosion control measures implemented at most of these study sites were effective in preventing construction-related adjustments after one winter.

The environmental benefits of upgrading forest roads with rock surfacing to minimize turbid runoff during wet weather road use in northwestern California was recently evaluated by Toman and Skaugset (2007). In this study, suspended sediment concentration was lowest from treated segments where ruts were not produced in truck wheel paths, and formation of ruts was found to be a function of aggregate depth. Toman and Skaugset (2007) suggest designing the aggregate surface to resist rutting to minimize sediment delivery. In the Sierra Nevada, Coe (2006) reported that rock surfacing generally reduces road sediment production by an order of magnitude or more relative to unsurfaced roads.

NEW REGULATORY, MONITORING AND EDUCATIONAL APPROACHES

Although it is certain that today's road design, construction and management practices are a vast improvement over the practices used decades ago, there are still lingering issues regarding forest roads in California:

- Monitoring indicates that stream crossing installations on Timber Harvesting Plans are sometimes improperly implemented.
- Although road erosion can be effectively controlled by surfacing, not all high risk road segments at or near streams have been treated to reduce surface erosion.
- Research on road surface erosion has been focused in the Sierra Nevada. There are few data currently available for the Coast Ranges.

There are other important issues that are not discussed in this paper. For example, the implications of a general shift in California from even-aged to uneven-aged management due to wildlife and fisheries concerns have not been evaluated. Road density is generally higher on ownerships harvested repetitively with ground-based harvesting systems (Harris and Cafferata 2005).

Uneven-aged management can result in more intensive road use and a higher potential for surface erosion compared to even-aged management. Also, while this paper focuses on issues related to forest management, it is likely that there are other road problems that are more important in the long term than timber-related road issues. In particular, our observations reveal that there are often greater problems with roads associated with lands that are not subject to state regulatory controls, such as are found in rural subdivisions (Harris and Cafferata 2004, 2005).

To address these lingering issues, new regulatory, monitoring and educational approaches are being used. A Road Rules Committee of the State Board of Forestry and Fire Protection (BOF) is currently working on ways to improve, revise and reorganize the California Forest Practice Rules related to roads. A draft version of this major revision is expected to be available by May 2007. This effort has the potential to improve the effectiveness of road-related Forest Practice Rules by upgrading practices, as well as making them easier to implement and enforce (Brandow et al. 2006). Additionally, the BOF is currently considering adoption of rules for a voluntary Road Management Plan.

To arrive at a common understanding of forestry related impacts on water quality, an Interagency Mitigation Monitoring Program (IMMP) was established in 2005 with members from state agencies involved in timber harvesting plan review. The initial focus has been on developing field methods for determining the implementation and effectiveness of practices at higher risk (non-random) road-stream crossing sites and road segments that drain to crossings. Pilot project work completed in 2006 showed that improper installation of crossings and drainage structures near crossings is often the major cause of water quality problems. Preliminary conclusions from the pilot work are that improved implementation of practices can be accomplished with additional timber operator education and more frequent multi-agency crossing inspections, both during logging operations and immediately following completion of harvesting. It is anticipated that this program will improve the effectiveness of practices applied at higher risk sites associated with crossings.

Several manuals and visual aids on road management and restoration have been developed for agency personnel, industry foresters, consulting foresters, and other resource professionals (Weaver and Hagens 1994, Flanagan et al. 1998, Keller and Sherar 2003, Cafferata et al. 2004, MCRCD 2004, CDFG 2006, Kocher et al. in press). To reduce erosion from county roads, road maintenance manuals have been produced for five northwestern California counties (Sommarstrom 2002) and six central coast counties (FishNet 4C et al. 2004). In addition, numerous workshops sponsored by state agencies, University of California Cooperative Extension and professional forestry organizations have been held in the recent past to educate stakeholders on how to address legacy road problems, how to design and construct road-stream crossings, and how to monitor water quality in forested watersheds. Points that have been stressed at workshops include: (1) requiring adequate long-term road maintenance and winter maintenance work for crossings, (2) improving construction/maintenance of road drainage structures—particularly those built near crossings, (3) disconnecting existing roads from the stream system by removing the inside ditch and out-sloping roads with rolling dips where possible, (4) surfacing roads located near streams, and particularly at stream crossings, (5) decreasing spacing between road drainage structures, (6) placing new roads on or near ridges, away from streams and reducing the number of crossings, (7) improving crossing decommissioning techniques through training with experienced individuals, and (8) improving the design of road-stream crossings for wood, sediment, and 100-year stream flow passage.

It is highly likely that these new initiatives will incrementally improve the conditions and performance of forest roads in California. Perhaps the greatest uncertainty is whether or not forest management will continue to be the dominant land use in large portions of the state with commercial timberlands.

SUMMARY AND CONCLUSIONS

Watershed research and monitoring work in California has shown that roads and road stream crossings are usually the dominant source of management-related erosion in forested environments. Past work has shown that a relatively small proportion of the total road length produces most of the road-related sediment delivered to streams. Detailed field surveys are the main tool available to identify the road segments of greatest concern (Korte and MacDonald 2007, MacDonald et al. 2007). Public and private landowners are actively inventorying their road networks, prioritizing road segments requiring road improvement or decommissioning work, and completing projects. A considerable amount of road upgrade work has been completed to date with both public and private financing. While there are short-term impacts associated with road decommissioning, particularly at road-stream crossings, road treatments will reduce the long-term sediment production from older roads (Madej 2001). Improved operator practices are required for road-stream crossing installation at high-risk sites and at decommissioned crossing sites. Guidebooks and training workshops have, and will continue to be, used to improve stakeholder knowledge regarding road and crossing practices.

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FIGURES AND TABLES

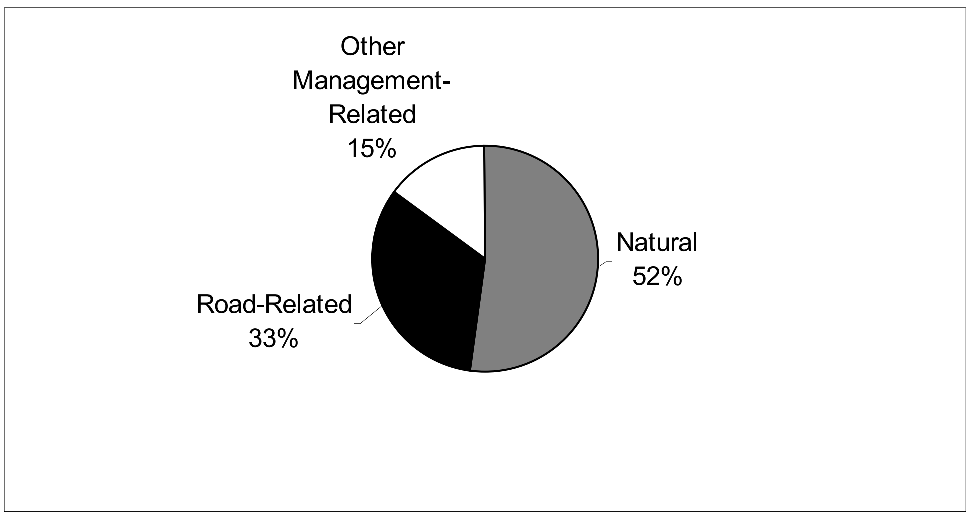

Figure 1. Distribution of natural and management-related sediment from 19 sediment budgets located in California.

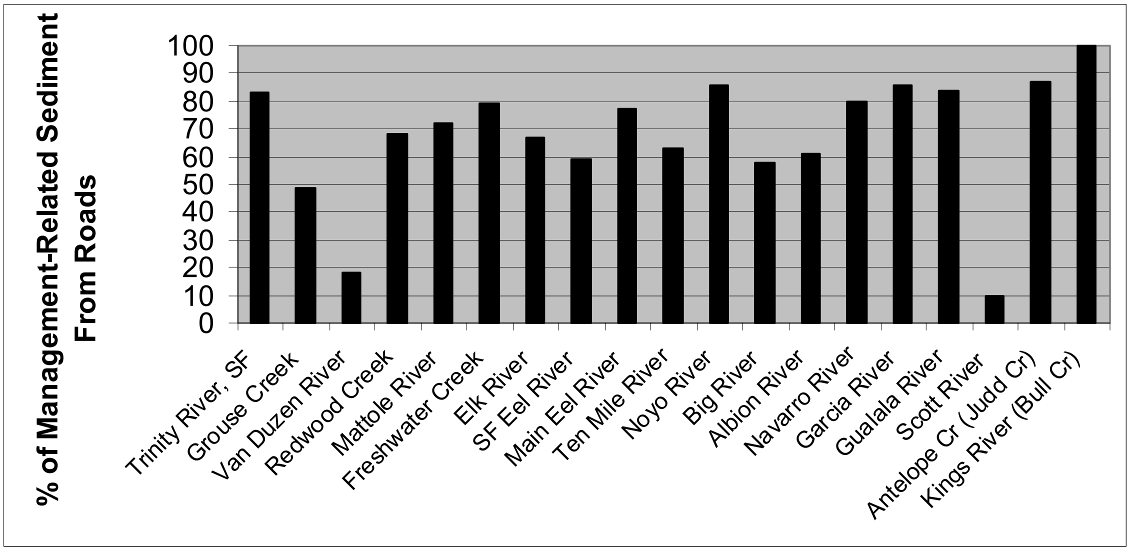

Figure 2. California sediment budgets from the northern Coast Ranges (16), Klamath Mountains (1), Cascade Range (1) and Sierra Nevada (1), showing the percent of management-related sediment estimated to derive from forest roads. The Redwood Creek sediment budget includes roads and skid trails; 68 percent of sediment for the Antelope Creek (Judd Cr.) sediment budget is estimated to result from long-term post-fire surface erosion; 14 of the 19 sediment budgets displayed were produced as part of TMDL documents for watersheds listed as impaired by the U.S. EPA.

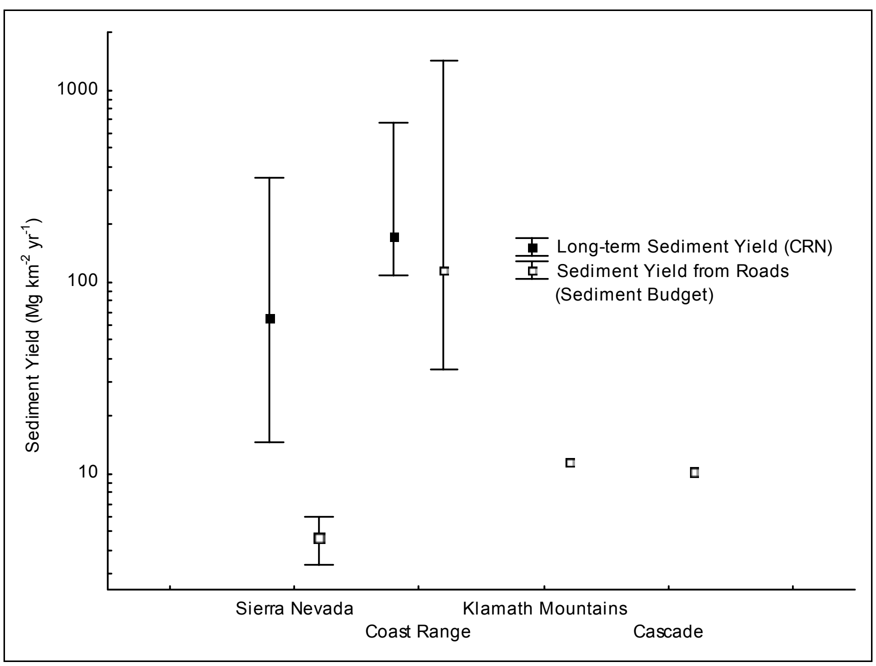

Figure 3. Comparison of millennial averaged sediment production rates derived from cosmogenic radio nuclide dating (CRN) to short-term sediment yields derived from sediment budgets produced for California watersheds. The boxes represent the median value and the error bars represent the range of values. CRN data is not available for the Klamath Mountains and the Cascade Range.

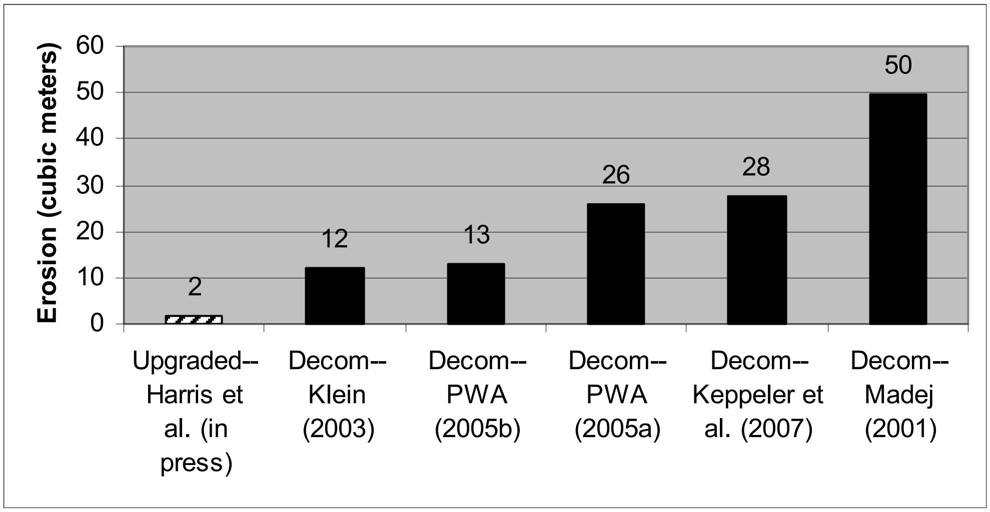

Figure 4. Comparison of post-treatment erosion volumes from decommissioned versus upgraded watercourse crossings.

Watershed	Geomorphic Province	Estimated Road-Related Erosion	Study Conducted	Reference
Kings River	Sierra Nevada	0.7 kg m^{-2} yr^{-1}	2004-2006	Korte and MacDonald 2007
American River	Sierra Nevada	0.9 kg m^{-2} yr^{-1}	1999	Coe 2006, MacDonald et al. 2004
Scott River, granitic tribs.	Klamath Mountains	33 kg m^{-2} yr^{-1}	1988-1989	Sommarstrom et al. 1990
Six Rivers National Forest	Coast Ranges	190 m^3 km^{-1}	1976	McCashion and Rice 1983
Redwood Creek--Cooper Cr	Coast Ranges	5200 m^3 km^{-1}	1954-1980	Weaver et al. 1995
Redwood Creek--Garret Cr	Coast Ranges	4730 m^3 km^{-1}	1956-1980	Best et al. 1995
Redwood Creek	Coast Ranges	180 m^3 km^{-1}	1997	Rice 1999
North Coast Region	Coast Ranges	250 m^3 km-1	1985-1986	Rice and Lewis 1991
Jordan Cr, Bear Cr, Elk River	Coast Ranges	720 m^3 km^{-1}	1998-1999	Weaver and Hagans 1999
South Fork Caspar Creek	Coast Ranges	200 m^3 km^{-1}	1967-1971	Krammes and Burns 1973
North Fork Caspar Creek	Coast Ranges	90 m^3 km^{-1}	1985-2000	Rice et al. 2004

Table 1. Road erosion rates from research studies conducted in California.