

Forest Roads in California

A Primer on Water Quality and Water Quantity Impacts

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Mission Statement

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Forest Roads in California: A Primer on Water Quality and Water Quantity Impacts was written by Mary Ann Madej, PhD. Dr. Madej is a geomorphologist based in north coastal California. She received her master's degree from the University of Washington under Dr. Tom Dunne, and her PhD degree from Oregon State University under Dr. Gordon Grant. She worked for the federal government for 35 years, examining erosion and sediment processes, primarily in the western United States, and is now a consultant on riverine and watershed analyses.



Cover Photo: ©Marcel Huijser, forest stream in Northern California

Cover sidebar photos from top to bottom:

- 1) forest road in Northern CA, ©Marcel Huijser;
- 2) culvert removal/stream crossing restoration, Shasta-Trinity National Forest, USFS photo;
- 3) overhead view of fish, USFS photo.



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The most generally valued and utilized "commodity" produced by California's forest lands is a sustainable, clean water supply (Reid, 1999; Jones *et al.*, 2009). Sixty percent of California's water originates from small streams in the Sierra Nevada (Eagan *et al.*, 2007). The source areas of headwater streams typically compose 60% to 80% of a catchment. This, along with the typical increase in precipitation with elevation, means that headwater streams generate most of the stream flow in downstream areas (MacDonald and Coe, 2007).

Unfortunately, extensive networks of both legacy and modern forest roads in headwater areas can impact water quantity, timing of flow, and water quality through many mechanisms. The United States has 4,000,000 miles of road (Forman *et al.* 2003) and the U.S. national forest road network consists of 370,000 miles of roads. In California alone, national forests manage almost 47,000 miles of road and an additional 37,000 miles of unpaved roads exist on private commercial timberlands (Cafferata *et al.*, 2007). California also has more than 1,000 major reservoirs, mostly in the central and northern portions of the state. Consequently, the extensive road network in headwater regions supplying water to the reservoirs has the potential of affecting beneficial uses of the water.

Forest road effects include:

A) Impacts on hydrology:

Roads commonly affect the flow of water through a watershed via several mechanisms: changes in soil properties; and the interception, concentration, and diversion of runoff.

- 1) In forested landscapes, rainfall typically infiltrates the soil and overland flow is rare. Compacted road surfaces decrease infiltration, leading to increased overland flow and surface runoff during rainfall and snowmelt (Coe, 2004).
- 2) Road cutbanks intercept slower moving subsurface water, transforming it to surface flow that is 10 to 10,000 times faster (Dunne, 1978) and rerouting it along roadside ditches, thereby increasing surface runoff. Interception of subsurface stormflow accounted for 7.3 times more runoff than the road surface in the snow-dominated Idaho Batholith (Megahan, 1972).
- 3) Road ditches and gullies concentrate flow from road surfaces and act as small stream channels during rainstorms, effectively increasing the length of the stream channel network. Flow paths become more connected and runoff rates can increase (Wemple *et al.* 1996; Croke and Mockler, 2001; Coe, 2004). In addition, the higher the channel connectivity, the higher the rate of sediment delivery to streams.
- 4) The configuration of road drainage structures can divert surface and subsurface water from flow paths that otherwise would be taken in the absence of a road (Wemple *et al.*, 1996). For example, when culverts become blocked, flow can be diverted to road ditches and to other channels downslope (Best *et al.*, 1995; Furniss *et al.*, 1998).

B) Impacts on water quantity

The combination of the above factors may lead to an increase in the frequency and magnitude of peak runoff discharges and change base stream discharges, particularly in small watersheds (Megahan, 1972; Harr *et al.*, 1975; King and Tennyson, 1984; Furniss *et al.*, 1991; Wemple *et al.*, 1996; Jones and Grant, 1996; Forman *et al.* 2003; Endicott 2008). Roads may also increase total runoff and decrease the time to peak runoff from major storms or snowmelt (Elliot, 2000). Nevertheless, the magnitude of road effects on peak flows is debated in the literature (Ice *et al.*, 2004; Coe, 2004). On a watershed scale, forest roads are usually associated with timber harvest, making it difficult to separate the effects of roads alone on water quantity (Thomas and Megahan, 1998). The hydrologic impact depends on the portion of the forested watershed area occupied by roads, road design, the degree of hydrologic connectivity, and soil properties.

With dwindling water supplies, some land managers are turning to active forest management as a possible means of augmenting water yield. Although forest harvest can increase water yield, such increases are often small and short-lived, and are less when water is most needed, such as in dry years and in dry areas. The combination of road infrastructure and widespread timber harvest needed to augment water yields often impairs water quality (Jones *et al.* 2009).

C) Impacts on water quality:

Forest roads are a major source of both chronic and episodic erosion and sediment delivery to streams nationwide (Endicott, 2008). Roads may divert sediment from the paths it follows in the natural landscape (Forman *et al.*, 2003). Both fine- and coarse-grained sediment as well as other pollutants enter the channel network through several types of road-related erosion mechanisms.

- 1) High traffic levels on unpaved roads can break down road surface material, increasing the supply of fine sediment that is washed off the road during the rainy season. Chronic surface erosion from road surfaces, cutbanks, and ditches is well documented and is often the dominant source of road-related sediment input to streams (see Endicott, 2008). Sheetwash and rilling are common on compacted, unpaved roads. Surface erosion varies widely, depending on climate, topography, road design, and road surface material (MacDonald and Coe, 2008).
- 2) Fine-grained sediment washed off the surface of unpaved roads leads to increased turbidity in the receiving streams. Turbidity from forest roads can increase treatment costs for municipal drinking water supplies (Madrone and Stubblefield, 2012) and increase settleable materials in receiving streams.
- 3) Surface runoff from roads can contain petroleum-based contaminants and other pollutants (such as herbicides, pesticides, insecticides, and fire retardants) (National Research Council, 2008). Hazardous chemical spills from vehicle accidents can contaminate streams adjacent to roads (Gucinski *et al.*, 2001). In the Umpqua National Forest, blue-green algae blooms in a popular lake have been associated with increased human development (Jones *et al.* 2007) although roads as an influence on nutrient input have not been isolated from other factors.
- 4) Road-stream crossings are vulnerable sites in the forest road transportation network. Culverts can be overwhelmed by high flows, or plug with sediment and wood. When the crossing fails,

the road prism commonly washes out, introducing sediment to streams and rivers. Crossing failures can lead to debris torrents or gullies downslope of the failure, incorporating more material than just the road prism (Furniss *et al.*, 1998). Surface runoff that exceeds the capacity of a culvert can be diverted down the roadway, causing more gullies and channel erosion (Best *et al.*, 1995; Furniss *et al.*, 1997).

- 5) Road construction on hillsides changes the mass balance by cutting benches into the terrain and moving materials onto fill slopes. The cuts remove weight and fills add weight. This change in the distribution of mass on the hillslope can initiate landsliding (de la Fuente and Elder, 1998). Oversteepened road cuts and road fills are particularly susceptible to mass failure, especially when soils become saturated.
- 6) Common mass movement features in forested mountain regions are shallow debris slides, deep-seated slumps and earthflows, and rapid debris flows. Many studies have documented an increase in landslide rates associated with forest roads. Rates of road-related landslides in the western U.S. and New Zealand were 30 to 346 times greater than the background rate on undisturbed lands (Sidle *et al.*, 1985). More recent studies showing similar results are summarized in Endicott (2008). Landslides that enter the channel network contribute coarse material (ranging from sand to boulders) to streams and rivers. A portion of this material is transported downstream as bedload. The amount of bedload transport is dependent on flow, channel slope and the size of material.
- 7) Not all material eroded from forest roads reaches a watercourse. Road fill failures may travel down a hillslope and be deposited on the forest floor rather than in a stream channel. In arid areas, material from hillslope failures may be deposited in alluvial fans and not be transported to a perennial river. Sediment delivery depends on multiple factors (such as road location, hydrologic connectivity, the volume of water available for sediment transport, effectiveness of sediment traps, and slope steepness) (Endicott 2008).

D) Reservoir storage and sedimentation

Reservoirs are sustainable only as long as they offer sufficient water storage space to achieve their design objectives. Life expectancy of reservoirs related to sedimentation is a measure of reservoir sustainability. Annual loss of reservoir capacity in California is 0.81 – 1.2 percent (Graf *et al.*, 2010). Consequently, increases in sediment yield, such as those associated with road-related erosion, will shorten the life expectancy of reservoirs. Specific rates of reservoir infilling depend on the contributing drainage area, trap efficiency, size of reservoir, and particle size and quantity of sediment input. For example, the reservoir upstream of Sweasey Dam on the Mad River in north coastal California prematurely filled with sediment and the 55-ft. high dam was subsequently removed in 1970. In this case naturally high sediment loads entering the reservoir were exacerbated by logging, associated road construction, and grazing (Mount, 1995).

E) Spatial and Temporal Scales

Effects of roads span several spatial scales, from site-specific increases in overland flow to potential basin-wide changes in flow routing due to increased hydrologic connectivity. Impacts from roads

can also span decades as legacy roads and skid trails continue to “bleed” sediment (Cafferata *et al.*, 2007; Sullivan *et al.*, 2012). Mass movements related to roads may only be activated years after road construction when a large storm occurs.

F) Regional differences:

California has an amazing diversity of landscapes, and specific influences of forest roads differ by geologic region and geomorphic terrain. California has 11 geomorphic provinces (geologic regions displaying a distinct landscape or landform): the Coast Ranges, Klamath Mountains, Cascade Range, Modoc Plateau, Basin and Range, Sierra Nevada, Great Valley, Mojave Desert, Transverse Ranges, Peninsular Ranges and Colorado Desert (California Geologic Survey, 2002). The arid and semi-arid areas do not support forests, so forest roads associated with timber harvest and forest management are not a concern there. Even within a single geologic region, certain geomorphic features are naturally more unstable and roads crossing these features are more susceptible to failure. Such features include headwater swales, steep inner gorges, breaks-in-slope, and former landslide deposits.

- 1) In some geologic regions, roads have an especially strong impact on sediment production. Decomposed granite (DG) is highly weathered granitic rock that has broken down to coarse sand and gravel (grus), and soils derived from DG are highly erodible. Saturated decomposed granite has essentially no cohesion (Durgin, 1977), so is susceptible to debris slides. DG is found in places where exposed granitic batholiths have weathered and eroded. In California, examples of DG terrain are seen in the Sierra Nevada, the Tahoe basin, the Trinity Alps, and parts of the mountains to the east of San Diego. Road cuts in decomposed granitic soils exhibit high erosion rates, and in the Scott River basin this accounted for 64 percent of road-related erosion (Sommarstron *et al.*, 1990), and roads in general contributed 82 percent of management-related sediment in this area. A dramatic example of high erosion in DG is found in Grass Valley Creek in Trinity County. In the 1964 flood, following a period of extensive timber harvest and road construction, Grass Valley Creek contributed more than 1,000,000 yd³ of sand and gravel to the Trinity River (TCRCD, 1998), coating the cobble-bedded river with eroded granitic grus. Road-related problems, including gullies and surface erosion, accounted for at least 59 percent of the total erosion potential identified in a sediment source inventory of Grass Valley Creek, and the USDA SSC (1992) recommended that the most effective way to reduce these risks is by redesigning or removing poorly located roads. In response to the high erosion rates in this DG watershed, Buckhorn Sediment Dam, a large sediment basin in the headwaters of the creek, and three sediment ponds near the mouth of the creek were constructed to trap the sand and protect downstream resources. But road treatments were a priority for reducing sediment production. Land managers implemented important mitigation efforts on priority access roads (e.g. outslipping, culvert upgrades), while also decommissioning more than 40 miles of roads (TCRCD, 1998) to help reduce sediment delivery to the streams within the Grass Valley Creek watershed.
- 2) Episodic disturbances such as high rainfall and large floods can initiate mass movement on roads in susceptible terrains. In the Klamath Mountains in 1997, floods with recurrence intervals of 14-18 years occurred on the Shasta, Scott and Klamath Rivers (de la Fuente and Elder, 1998). Klamath National Forest staff inventoried 1100 resulting landslides and the relationship to roads in the watersheds. Landslide density (landslides per square mile) averaged 0.59 across the landscape, but was 7.34 in road corridors. Sensitive lands, such as the Rattlesnake Terrane (a

sheared serpentinite mélangé) and old landslide deposits, were most susceptible to landsliding, especially debris slides. Road corridors within susceptible terrains had the highest landslide densities, 11.5 to 91.9 (de la Fuente and Elder, 1998).

- 3) Much of the Coast Range is underlain by the Franciscan Complex, which is composed predominantly of graywacke (sandstone) and siltstone. The northern Coast Ranges are dominated by landslide topography and are susceptible to debris flows and debris slides (Cafferata *et al.*, 2007). Deep-seated earthflows are common in highly sheared Franciscan mélangé (Muhs *et al.*, 1987). Although roads probably do not affect the movement rate of earthflows (where the failure plane can be 20 ft. deep or more) the highly disrupted material of earthflows is extremely vulnerable to gully erosion (Nolan and Janda, 1995), due to poor road drainage as well as natural channel shifting. Episodic gully erosion from diverted road-stream crossings was greater than surface erosion in the Redwood Creek basin in this region (Hagans *et al.*, 1996). The younger Wildcat Formation, overlying the Franciscan Complex in the Eel River area, is an especially erodible sequence of mudstones and siltstones where high rates of road-related erosion have been measured (Sullivan *et al.*, 2012).
- 4) The Cascade Range is a chain of volcanoes that extends through Washington, Oregon and northern California. Mt. Shasta, a glacier-mantled volcano, rises 14,162 ft. and is a major source of water to the local rivers. A gigantic landslide deposit originating from an ancient volcano covers more than 180 square miles in Shasta Valley. Lassen Peak is the southern end of the Cascades and last erupted in the early 1900's. The volcanic bedrock is porous, thus melting snow percolates down through lava tubes and fractures and feeds springs farther downslope. The spring-fed nature of the hydrology results in less surface erosion than in the Coast Range. The California North Coast Regional Water Quality Control Board (2006) listed the Shasta River as temperature-impaired and dissolved oxygen impaired, but not sediment impaired.
- 5) In the central Sierra Nevada, road surface erosion is the dominant erosional process on forest roads and mass wasting is infrequent (Cafferata *et al.* 2007). On National Forest and private forest lands, sediment production rates were 16 times higher on unrocked road segments compared with rocked roads. The highest rates of erosion came from road segments with unusually high rates of subsurface stormflow interception by road cutslopes (Coe, 2006).
- 6) In Southern California the Peninsular Ranges consist of a series of mountain ranges with granitic rock intruding older metamorphic rocks. In general, metamorphic rocks are more resistant to erosion than the sedimentary rocks of the Coast Range. Fire is common in chaparral terrain in this region. Post-fire erosion has been well studied here, and treatments focus on decreasing overland flow and impounding runoff (Wohlgemuth, 2003). Sheetwash, rilling and gullying commonly occur after fires. Road-related erosion has not been as thoroughly investigated, although the Cleveland, Angeles, Los Padres and San Bernardino National Forests are developing criteria to decommission roads and trails on forest lands. They use the Erosion Hazard developed by the Natural Resource Conservation Service Soil Inventory and number of road-stream crossings as part of the evaluation process to determine erosion risks of roads.

G) Cumulative watershed effects

A single road across a hillslope may produce minimal sediment, but if other roads crisscross that hillslope, the roads may interact and generate cumulative impacts. For example, a small stream

crossing failure on an upper hillslope may initiate additional failures at several downslope crossings, and thus the negative impacts accumulate and cascade down the hillslope into the channel below. Cumulative watershed effects can also result from the interaction of diverse land-use activities, such as grazing, timber harvest, recreation and the associated roads (Reid, 1993, 1998). The possible cumulative effect of increasing discharge due to the presence of roads in a watershed is still being debated in the scientific literature.

H) Road-related Erosion vs. Post-wildfire Erosion

In mountainous areas, wildfire can cause significant erosion. Intense rainfall on severely burned hillslopes can cause surface erosion and debris flows. Comparisons of erosion caused by wildfires with erosion caused by roads are few. A study of surface erosion in the Sierra Nevada on both roads and severely burned areas showed that sites burned at a high severity had a mean sediment production rate of 1.1 kg/m² in the first rainy season following fires. Sediment production rates dropped quickly, and were an order of magnitude less the second year after a fire, and the third year sediment production rates were another 70% lower. Mean sediment production rate from unpaved roads (both native and rocked) was 0.9 kg/ m² and native surface roads produced 10-50 times more sediment than rocked roads (MacDonald *et al.*, 2004). Although surface erosion from roads was less than the first-year post-fire erosion, surface erosion from roads is an annual process, causing chronic problems, whereas post-fire erosion is an episodic occurrence that decreases rapidly with time.

Even though the visual scar of a fire across a landscape is obvious, not all sediment produced by post-fire erosion is delivered to rivers, sediment production declines rapidly within a few years, and a fire may not recur in the same watershed again for decades. In contrast, forest roads commonly are an accepted part of the landscape, and yet they can “bleed” sediment year after year, and cumulatively may have a larger effect than a fire over the lifespan of the road. The relative contribution of sediment to rivers from wildfires and from forest roads needs to be evaluated on a watershed-by-watershed basis.

I) Future Changes in the Hydrologic Regime

Water managers in California are facing challenges as the hydrologic regime in mountainous terrain changes as a result of climate change. Spring snowmelt is the most important contribution to many rivers arising in the Sierra Nevada, Cascades, and Klamath Mountains. A shift in the timing of springtime snowmelt towards earlier in the year has already been observed for many western rivers between 1948-2000, and models predict a continuation of this trend (Stewart *et al.*, 2004). Climate change may be reducing streamflow from reference forested watersheds in the Pacific Northwest (Mote *et al.*, 2003). The hydrologic impacts of roads may exacerbate water supply problems associated with changing snowmelt regimes. In addition, climate change may be increasing the severity and or frequency of severe pacific storms, which can increase the potential for road failures and associated landslides.

J) Mitigation Alternatives

Water quality problems associated with roads can be addressed through several methods. The methods vary in large part based on funding and projected future use of any given road.

For forest roads that are needed as part of a transportation network, road treatments (sometimes called “stormproofing”) include outsloping or crowning the road surface, adding surface rock,

resizing and replacing culverts, armoring culvert fills, constructing rolling dips, installing ditch relief culverts, upgrading bridges, reducing traffic under wet conditions, using soil bioengineering techniques to stabilize slopes, and scheduling regular maintenance. Gullies and landslides can be deterred by decreasing runoff at discharge points, draining the road to planar or convex hillslopes, and providing energy dissipation at outlets.

For roads that are no longer needed or that traverse especially sensitive lands, physically obliterating or stormproofing the road is recommended. There are many possible treatments and different agencies use different terminologies for those treatments. Road closure and abandonment may be the easiest and least expensive techniques, but they do not prevent many erosion problems, as they rarely include any physical treatment on the ground to reduce hydrologic impacts. Physically disconnecting the road drainage system from the stream/hydrologic system is the most important first step of any road obliteration efforts. Treatment typically involves removing culverts, reshaping stream crossings, installing drainage, and mulching or revegetating roadbeds as needed, while leaving the bulk of the road prism intact. Full recontouring is a more complete form of road removal, including full recontouring of the road bed (ideally with the recovery of buried topsoil where possible) to mimic the shape of the original topography as well as restoring stream crossings. Hydrologically disconnecting roads and fully decommissioning or recontouring roads reduce sediment input from roads, although even these treatments do not completely eliminate erosion on steep, lower hillslope roads (Switalski *et al.* 2004).

These road treatments are referred to by many different names. For example, the US Forest Service can use road decommissioning to mean anything from posting a closure sign to fully recontouring the road. In addition, public land managers may use different terminology depending on the legal status of a road. The Forest Service, for example, might use the same physical treatment on a road, but the road would be considered “in storage” if they are leaving it on the formal transportation system, while it might be considered “decommissioned” if they are removing it from the transportation system. Mitigation should be based on the actual physical treatment, regardless of terminology, to effectively address the particular impact of concern.

Recent research by the USDA Forest Service Intermountain Research Station shows significant beneficial effects from both stormproofing and full road recontour. For example, in a study that included sites in California (as well as five other western states), researchers found that both stormproofing and full recontouring significantly reduced sediment delivery to streams post-treatment and specifically post-storm. Recontouring reduced sediment delivery by 80%, while stormproofing reduced sediment delivery by 67% (Wildlands CPR, 2012).

o Study locations: MT, ID, OR, WA, CA, UT

K) Regulatory Efforts

Under section 303(d) of the Clean Water Act, states are required to identify all water bodies that do not meet water quality standards. For those “impaired” watersheds, the states must develop and implement Total Maximum Daily Loads (TMDLs) or implement another program that will result in the attainment of water quality standards. A key component of TMDLs is a source assessment, which includes sediment contributions from forest roads. A host of TMDLs have been completed across California. For the North Coast Region alone, 20 sediment TMDLs have been completed, which show the road system averages 57 percent of the management-related sediment load (Buffleben, 2012). Correct implementation of Best Management Practices (BMPs) on the currently

used road network can substantially mitigate nonpoint pollution for forestry activities at the site scale, although BMPs are not 100% effective (Jackson *et al.* 2004, cited in Endicott, 2008). Treatment of abandoned or legacy roads is commonly needed as well to reduce road-related sediment production on a basin scale.

Summary

Extensive networks of both legacy and modern forest roads in headwater areas can impact water quantity, timing of flow, and water quality through multiple mechanisms. The specific impact of a road on water quality depends on several factors, however. Road effects differ by landscape position (ridgetops, inner gorge, valley floor, etc.), by soil and geology, and by climate. Even within the same region, effects differ depending on road size, design, construction, age, usage and maintenance. Nonetheless, with so many forest roads existing in California's headwaters, the cumulative impacts of the overall forest road system to both water quality and quantity are highly problematic. These impacts, especially sediment delivery, are both ecological and fiscal, with increasing impacts to municipal water supplies and reservoirs potentially leading to increasing mitigation and/or restoration costs.

Road assessment protocols have been developed to evaluate potential impacts of forest roads under specific landscape conditions, and to assess the specific role roads play in contributing sediment to streams (e.g. USDA Forest Service, 1999; Black 2012). Such road assessments can help guide land management decisions. Land and water managers should pay particular attention to the condition and location of the roads within the headwaters areas to ensure appropriate mitigation and restoration steps are being taken, including road reclamation and stormproofing, both to reduce the impacts of roads on water quality, and to ensure safe and reliable road access for both resource management and recreational purposes.

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Citations and Extended Bibliography
(with some annotations)

Barrett, B., R. Kosaka, and D. Tomberlin. 2012. Road surface erosion on the Jackson Demonstration Forest: Results of a Pilot Study. P. 13-21 in Proceedings of the Coast Redwood Forests in a Changing California: A symposium for scientists and managers. R.B. Standiford, T.J. Weller, D.D. Piirto, J.D. Stuart, eds. USDA Forest Service. General Technical Report PSW-GTR-238. Albany CA. 675 p.

Total sediment production (fine and coarse) ranged from 0.02 to 4.5 kg/m²/yr, based on a 3-yr pilot study of 10 road segments.

Best, D.W., H.M. Kelsey, D.K. Hagans, and M. Alpert. 1995. Role of Fluvial Hillslope Erosion and Road Construction in the Sediment Budget of Garrett Creek, Humboldt County, California. P. M1-M9 in Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. K. M. Nolan, H. M. Kelsey, and D.C. Marron, eds. U.S. Geological Survey Professional Paper.

Black, T.A., R.M. Cissel, and C.H. Luce. 2012. The Geomorphic Road Analysis and Inventory Package (GRAIP) Volume 1: Data Collection Method. General Technical Report RMRS-GTR-280WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 110 p.

This report is one of several related reports about the Geomorphic Road Analysis and Inventory Package (GRAIP). This report explains data collection methodologies, while others explain office protocols, quality control, etc. Yet other reports (see Wildlands CPR below) provide an example of how GRAIP has been used both to assess road mitigation and decommissioning effectiveness, and to assess road-derived sediment delivery in sample watersheds in the northwest and in the intermountain areas.

Buffleben, M.S. 2012. Total maximum daily loads, sediment budgets, and tracking restoration progress of the North coast Watersheds. P. 23-31 in Proceedings of the Coast Redwood Forests in a Changing California: A symposium for scientists and managers. R.B. Standiford, T.J. Weller, D.D. Piirto, J.D. Stuart, eds. USDA Forest Service. General Technical Report PSW-GTR-238. Albany CA. 675 p.

This compares TMDL sediment loading estimates in 20 north coastal California watersheds. A majority of the anthropogenic sediment loading is associated with roads.

Cafferata, P.H., D.B.R. Coe, and R.R. Harris. 2007. Water resource issues and solutions for forest roads in California. *Hydrological Science and Technology*. 23(1-4):39-56.

The authors conducted a literature review of the effects of forest roads on water resources in four regions in California: the northern Coast Range, the Sierra Nevada, the Klamath Mountains, and the Cascade Range. Most road erosion studies in California have been conducted in the northern Coast Range, much of which is underlain by the highly erodible Franciscan Complex. Here, erosion from roads is primarily associated with mass wasting. In the central and southern Sierra Nevada, mass wasting is infrequent and road surface erosion is more prominent.

Cafferata, P.H. and L.M. Reid. 2013. Applications of long-term watershed research to forest management in California: 50 years of learning from the Caspar Creek Experimental Watersheds. California Forestry Report No. 5.

Key research findings covering 50 years of monitoring in the Caspar Creek watersheds are summarized. These include studies in changes in peak flows, low flows, wood inputs and sediment loadings.

California Geological Survey. 2002. Note 36. Sacramento, CA. 4 p.

California North Coast Regional Water Quality Control Board. 2006. Staff Report for the action plan for the Shasta River watershed temperature and dissolved oxygen total maximum daily loads. Santa Rosa, CA.

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

On National Forest and private forest lands, sediment production rates were 16 times higher on unrocked road segments compared with rocked roads. The highest rates of erosion came for road segments with unusually high rates of subsurface stormflow interception by road cut-slopes.

Coe, D. 2004. The Hydrologic Impacts of Roads at Varying Spatial and Temporal Scales: A Review of Published Literature as of April 2004. Washington State Department of Natural Resources. CMER #04-410. 30 p.

This literature review summarizes site-scale changes in hydrology due to roads (e.g., increased Hortonian overland flow (when rainfall rates exceed soil infiltration rates, resulting in sheetwash) and basin-scale changes (e.g., connectivity). It also discusses the contradictory results of several studies of changes in peak flow due to road presence.

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.

DeGraff, J.V., B. Roath, and E. Franks. 2007. Monitoring to improve the understanding of herbicide fate and transport in the southern Sierra Nevada, California. P. 353-360 in M.J. Furniss, C.F. Clifton, K.L. Ronnenberg, eds. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference*. USDA Forest Service PNW-GTR-689. 577 p.

Reforestation on the Sierra and Stanislaus National Forests included the use of the herbicide hexazinone. Monitoring detected hexazinone in both groundwater and surface runoff, but levels were below the concentration established by the State of California as a water quality concern.

De la Fuente, J. and D. Elder. 1998. The Flood of 1997 Klamath National Forest. Phase I Final Report. USDA Klamath National Forest. Yreka, CA. 242 p.

Episodic disturbances such as large floods can initiate mass movement on susceptible terrains. In 1997 floods with recurrence intervals of 14-18 years occurred on the Shasta, Scott and Klamath Rivers (de la Fuente and Elder, 1998). Klamath National Forest staff inventoried 1100 resulting landslides and the relationship to roads in the watersheds. Landslide density (Landslides per square mile) averaged 0.59 across the landscape, but was 7.34 in road corridors. Sensitive lands, such as the Rattlesnake Terrane, (a sheared serpentinite mélange) and old landslide deposits,

were most susceptible to landsliding, especially debris slides. Road corridors within susceptible terrains had landslide densities of 11.5 to 91.9.

Doyle, J. and G. Ketcheson. 2007. Lessons learned from management response to flood-damaged roads in the Western Washington Cascades. p. 291-296. in M.J. Furniss, C.F. Clifton, K.L. Ronnenberg, eds. Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference. USDA Forest Service PNW-GTR-689. 577 p.

A post-flood assessment of road damage identified several types of problems: undersized road crossing structures, and improper spacing, orientation, location, and number of drainage structures. Rather than taking the typical "replace-in-kind" approach of the Federal Highways Emergency Relief Federally-Owned (ERFO) Program, the Mt. Baker-Snoqualmie National Forest developed a suite of road restoration treatments to address flood-damaged roads.

Dunne, T. 1978. Field studies of hillslope flow processes, Chapter 7, In Hillslope Hydrology, (ed. M. J. Kirkby), Wiley, London, 227-293.

Durgin, P.B. 1977. Landslides and the weathering of granitic rocks. Geological Society of America. *Reviews in Engineering Geology*. V3:127-131. Boulder, CO.

Dutton, A.L., K. Loague, and B.C. Wemple. 2005. Simulated effect of a forest road on near-surface hydrologic response and slope stability. *Earth Surface Processes and Landforms*. 30:325–338.
doi: 10.1002/esp.1144

A three-phase modelling effort was employed to test whether a near-surface permeability contrast, caused by surface compaction on forest roads, can result in diverted subsurface flow paths that produce increased up-slope pore pressures and slope failure. The permeability contrast associated with the forest road in this study led to a simulated altering of slope-parallel subsurface flow with increased pore pressures up-slope of the road and, for a large rainfall event, a slope failure prediction.

Eagan, S.M., C.T. Hunsaker, C.R. Dolane, M.E. Lynch, and C.R. Johnson. 2007. Discharge and Sediment Loads at the Kings River Experimental Forest in the Southern Sierra Nevada of California. In M.J. Furniss, C.F. Clifton, K.L. Ronnenberg, eds. Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference. USDA Forest Service PNW-GTR-689. 577p.

Stream discharge, sediment loads and water chemistry are being monitored on eight small perennial watersheds in the Sierra Nevada. Baseline conditions and variability are being quantified before harvest begins in six of the watersheds. This study site should prove to be useful in the future to document effects of fire, thinning, and timber harvest.

Endicott, D. 2008. National Level Assessment of Water Quality Impairments Related to Forest Roads and Their Prevention by Best Management Practices. Great Lakes Environmental Center. Traverse City, MI.

A comprehensive assessment and literature review related to road impacts to water quality and the effectiveness of Best Management Practices. This report, prepared for the EPA Office of Water Management, focused on three specific areas of interest to EPA: 1) impacts of forest roads on water quality and aquatic resources; 2) BMPs for forest roads,

including descriptions, effectiveness, shortcomings and costs; and 3) state BMP programs already in effect for forest roads.

Forman, R.T.T. *et al.* 2003. Road Ecology: Science and Solutions. Island Press. Covelo, CA. 481 p.

Fourteen authors collaborated to discuss the history of U. S. road construction and transportation planning, and the effects of roads on vegetation, wildlife, water quantity and quality, and aquatic ecosystems.

Furniss, M.J.; T.D. Roelofs, and C.S. Yee, 1991. Road construction and maintenance. In W.R. Meehan, ed. Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitats. Spec. Publ. 19. Bethesda, MD: American Fisheries Society: 297-323.

Furniss, M.J., T.S. Ledwith, M.A. Love, B.C. McFadin, S.A. Flanagan. 1998. Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California. USDA Forest Service San Dimas Technology and Development Center. San Dimas, CA. Publication #: 9877 1806—SDTDC.

Following a large flood in 1996, road crossing failures were inventoried in several national forests in Washington, Oregon and California. Road fill was eroded at 79% of the crossings where streamflow overtopped the road. Streamflow was diverted out of its natural channel at 48% of the failed crossings.

Furniss, M.J., M.A. Love, and S.A. Flanagan. 1997. Diversion Potential at Road-Stream Crossings. USDA Forest Service, San Dimas Technology and Development Center, 9777-1814, 12pp.

Diversion potential at stream crossings is defined, consequences are discussed, and road design recommendations to prevent diversions are proposed.

Gomi, T., D.R. Moore, and M.A. Hassan. 2005. Suspended Sediment Dynamics in Small Forest Streams of the Pacific Northwest. *Journal of the American Water Resources Association* 41:877–898.
doi: 10.1111/j.1752-1688.2005.tb03775.x

This paper reviews suspended sediment sources and transport in small forest streams in the Pacific Northwest region of North America, particularly in relation to riparian management. It does not focus on road-specific erosion.

Graf, W.L., E. Wohl, T. Sinha, and J.L. Sabo. 2010. Sedimentation and sustainability of western American reservoirs. *Water Resources Research*. V46. W12535.

Data from the USGS Reservoir Sedimentation Survey Information system II from across the US were used to assess life expectancy of reservoirs. New England and Tennessee reservoirs had the longest life expectancies, whereas the shortest was in the interior west.

Gucinski, H., M. Furniss, R. Ziemer, and M. Brookes. 2001. Forest roads: A Synthesis of Scientific Information. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Hagans, D.K., W.E. Weaver, and M.A. Madej. 1986. Long-term on-site and off-site effects of logging and erosion in the Redwood Creek basin, Northern California. P.38-66 in National Council for Air and Stream Improvement (NCASI) Tech. Bull. No. 490.

- Harden, D. R., S.M. Colman, and K.M. Nolan. 1995. Mass movement in the Redwood Creek basin, Northwestern California. Chapter G in: Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. K.M. Nolan, H.M. Kelsey, and D.C. Marron, eds. U.S. Geological Survey Professional Paper.
- Jones, J.A. and G.E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, Western Cascades, Oregon. *Water Resources Research*. 32(4): 959-974.
This study looked at the effects of clear-cutting and roads on peak discharge in small and large basins during small and large rainfall events. The authors concluded that storm hydrographs responded significantly differently to harvest with roads than just clear-cutting alone. They speculated that the hydrologic connectivity of roads was the mechanism to produce large storm peaks.
- Jones, J.A., F.J. Swanson, B.C. Wemple, and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology*. 14(1)76-85.
DOI: 10.1046/j.1523-1739.2000.99083.x
The authors outline how road networks interact with stream networks at the landscape scale and, based on examples from recent and current research, illustrate how these interactions might affect biological and ecological processes in stream and riparian systems. Road networks appear to affect floods and debris flows and thus modify disturbance patch dynamics in stream and riparian networks in mountain landscapes.
- Jones, M., J. Eilers, and J. Kann. 2007. Water quality effects of blue-green algal blooms in Diamond Lake, Oregon. P.102-110 in M.J. Furniss, C.F. Clifton, K.L. Ronnenberg, eds. Advancing the fundamental sciences: Proceedings of the Forest Service National Earth Sciences Conference. USDA Forest Service PNW-GTR-689. 577 p.
- Jones, J.A., G.L. Achterman, L.A. Augustine, I.F. Creed, P.F. Folliott, L. MacDonald, and B.C. Wemple. 2009. Hydrologic effects of a changing forested landscape – challenges for the hydrological sciences. *Hydrological Processes*. 23:2699-2704.
- Keller, G. and J. Sherar. 2003. Low-Volume Roads Engineering Best Management Practices Field Guide. Produced for the US Agency for International Development. 182 p.
<http://www4.worldbank.org/afr/ssatp/Resources/HTML/LVSR/English/Added-2007/2003-LVR-Engineering-FieldGuide-USA-by-GKeller.pdf>
The manual describes BMPs that are designed to prevent failure and reduce maintenance needs and repair costs on low volume roads. These include controlling surface water, stabilizing the roadbed surface, stormproofing, and reducing mass wasting on roads.
- Keppeler, E. T. 2012. Sediment production in a coastal watershed: Legacy, land use, recovery, and rehabilitation. P.69-77 in Proceedings of the Coast Redwood Forests in a Changing California: A Symposium for Scientists and Managers. R.B. Standiford, T.J. Weller, D.D. Piirto, J.D. Stuart, eds. USDA Forest Service. PSW-GTR-238. Albany CA. 675 p.

A recent assessment of 1970's era roads showed that stream crossings eroded an average volume of 10 m³. Stream diversions were common, and many sites have the potential for future diversion and sediment delivery.

Keppeler, E. and J. Lewis. 2007. Understanding the hydrologic consequences of timber harvest and roading: Four decades of streamflow and sediment results from the Caspar Creek Experimental Watersheds. P.191-196 in M.J. Furniss, C.F. Clifton, K.L. Ronnenberg, eds. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference*. USDA Forest Service PNW-GTR-689. 577 p.

Mass wasting was predominantly associated with roads, landings, and tractor skid trails in the South Fork of Caspar Creek. Sediment yield increased in two basins after they were both clearcut and roaded, but road influence on sediment yield was not isolated.

Klein, R.D., J. Lewis, and M.S. Buffleben. 2012. Logging and turbidity in the coastal watersheds of northern California. *Geomorphology*. 139-140:136-144.

The authors conducted a regional analysis of turbidity response to forest management in north coastal California in 2005. The study related the turbidity value exceeded 10% of the time to various management and natural factors. They found that watershed area and the rate of timber harvest 10 to 15 years prior were statistically significant factors in predicting chronic turbidity, but that road density was not. (However, a more recent analysis using data sets for 2003 to 2011 could not replicate these results (Sullivan et al., 2012).

MacDonald, L. H. and D. B. R. Coe. 2007. Influence of Headwater Streams on Downstream Reaches in Forested Areas. *Forest Science*. 53(2):148-168.

The source areas of headwater streams typically compose 60% to 80% of a catchment. This, plus the typical increase in precipitation with elevation, means that headwater streams generate most of the streamflow in downstream areas. Headwater sources of water, fine sediment, and fine particulate organic matter are more likely to be delivered to downstream reaches than coarse sediment, woody debris, nutrients, or an increase in water temperatures. The complexity and temporal variability of channel-hillslope interactions, in-channel processes, and downstream conditions makes it difficult to rigorously link upstream inputs and anthropogenic activities to the condition of downstream resources.

MacDonald, L.H., D.B.R. Coe, and S.E. Litschert. 2004. Assessing cumulative watershed effects in the central Sierra Nevada: Hillslope measurements and catchment-scale modeling. P.149-157 in D.D. Murphy and P. A. Stine, eds. *Proceedings of the Sierra Nevada Science Symposium*, US DA Forest Service PSW-GTR-193. Albany CA. 287 p.

Surface erosion was measured during three wet seasons on roads, skid trails, off-road vehicle trails, fire-disturbed hillslopes and undisturbed sites. Sites burned at a high severity had a mean sediment production rate of 1.1 kg/ m² in the first rainy seasons following fires. Sediment production rates dropped quickly, and were an order of magnitude less the second year, and the third year sediment production rates were another 70% lower. Mean sediment production rate from roads was 0.2 kg/ m² and native surface roads produced 10-50 times more sediment than rocked roads. Mass wasting was not assessed in this study.

MacDonald, L.H. and D.B.R. Coe. 2008. Road sediment production and delivery: Processes and management. P.385-388 In *Proceedings of the First World Landslide Forum*, United Nations University, Tokyo, Japan. International Consortium on Landslides, Japan.

Rates of erosion from unpaved roads from across the US and other countries are compared. Both surface erosion rates and road-induced landslide rates are compiled. Sediment delivery to streams occurs primarily at road-stream crossings.

Madrone, S S. and A.P. Stubblefield. 2012. Fine sediment sources in coastal watersheds with uplifted marine terraces in northwest Humboldt County, California. *In* Proceedings of the Coast Redwood Forests in a Changing California: A Symposium for Scientists and Managers. USDA Forest Service PSW-GTR-238. Albany, CA. 675 pp.

Road-related turbidity in Luffenholz Creek has increased drinking water treatment costs for the city of Trinidad, California. Treatment has the potential for creation of a dangerous by-product, chloro-tribalomethans, that can remain in the treated water. High turbidities can lead to water shortage emergencies in this small city. Grab samples during storms were collected at the mouth of the creek and several tributaries from 2006 to 2009. Highest turbidities were associated with high densities of unpaved riparian roads.

Megahan, W.F. 1972. Subsurface flow interception by a logging road in mountains of Central Idaho. P.350-356 *in* Watersheds in Transition. Proceedings of a Symposium on "Watersheds in Transition." Fort Collins, Colorado, June 19-22, 1972. AWRA. Urbana, Illinois.

Miller, A. and J. de la Fuente. 2007. A comparison of Northern California TMDLs. P.559 *in* M.J. Furniss, C.F. Clifton, K.L. Ronnenberg, eds. Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference. USDA Forest Service PNW-GTR-689. 577 p.

A lack of standardization among TMDL assessments makes comparison of sediment sources and loadings difficult.

Mirus, B.B., B.A. Ebel, K. Loague, and BC. Wemple. 2007. Simulated effect of a forest road on near-surface hydrologic response: redux. *Earth Surface Processes and Landforms*. 32:126–142. doi: 10.1002/esp.1387

An Integrated Hydrology Model (InHM) was employed to conduct both three- and two-dimensional (3D and 2D) hydrologic-response simulations for a small upland catchment located within the H. J. Andrews Experimental Forest in Oregon. Results identify subsurface stormflow as the dominant hydrologic-response mechanism and show the effect of the down-gradient forest road on both the surface and subsurface flow systems. The model illustrates the importance of convergent subsurface flow caused by roads, which can influence slope stability at the catchment scale.

Mote, P.W., E. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover. 2003. Preparing for climatic change: The water, salmon and forests of the Pacific Northwest. *Climatic Change* 61:45-88.

Mount, J.F. 1995. California Rivers and Streams: The Conflict between Fluvial Process and Land Use. University of California Press. Berkeley, CA. 359 p.

Muhs, D.R., R.M. Thorson, J.J. Clague, W.H. Mathews, P. McDowell, H.M. Kelsey. 1987. Pacific Coast and Mountain System. Chapter 13 *in* W.L. Graf, ed. Geomorphic systems of North America. Geological Society of America Centennial Special Volume 2. Boulder, CO.

National Research Council. 2008. Hydrologic Effects of a Changing Forest Landscape. National Academies Press. Washington, DC. http://www.nap.edu/catalog.php?record_id=12223

The Water Science and Technology Board of the National Research Council convened a committee to summarize the state of knowledge of forest hydrology, the effects of forest management, disturbances, grazing, and roads on hydrology, and directions for future management. Included is a discussion of cumulative effects and efforts to increase water yield through timber harvesting. Although forest harvest can increase water yield, such increases are often small and short-lived, and are less when water is most needed, such as in dry years and in dry areas. The combination of road infrastructure and widespread timber harvest needed to augment water yields often impairs water quality.

Nolan, K.M. and R.J. Janda. 1995. Movement and sediment yield of two earthflows, northwestern California. P.F1-F12 in K.M. Nolan, H.M. Kelsey, and D.C. Marron, eds., *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California*. U.S. Geological Survey Professional Paper 1454. Washington, DC. 16 pp.

Reid, L.M. 1999. Forest Practice Rules and Cumulative Watershed Impacts in California. Unpublished response to an inquiry from Assemblyman Fred Keeley. USDA Forest Service, Pacific Southwest Research Station, Redwood Sciences Laboratory, Arcata, California. 10 p.

Reid, L.M. 1993. Research and Cumulative Watershed Effects. U.S. Department of Agriculture, Forest Service PSW-GTR-141. Albany, CA. 118 p.

Riedel, M.S., L.W. Swift, Jr., J.M. Vose, and B.D. Clinton. 2007. Forest road erosion research at the Coweeta Hydrologic Laboratory. P.197-204 in M.J. Furniss, C.F. Clifton, K.L. Ronnenberg, eds. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference*. USDA Forest Service PNW-GTR-689. 577 p.

Erosion from forest roads in the southern Appalachian Mountains increase sediment yields. Nearly 100% of the sediment yield increase to streams following total forest harvest originated from stream crossings representing only 1% of the total watershed area and 17% of total road length. Erosion and sedimentation from forest road stream crossings may affect the sediment budgets of streams for decades.

Sidle, R.C., A.J. Pearce and C.L. O'Loughlin. 1985. Hillslope stability and land use. *Water Resources Monograph 11*. American Geophysical Union. Washington, DC. 140 p.

Sommarstron, S., E. Kellogg, and J. Kellogg. 1990. Scott River watershed granitic sediment study. Final report prepared for the Siskiyou County Resource Conservation District. Etna, CA.

Inventory of the Scott River basin showed that cutbank erosion in decomposed granite accounted for 64 percent of road-related erosion.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a 'Business As Usual' climate change scenario. *Climate Change* 62:217-232.

Sullivan, K., D. Manthorne, R. Rossen, and A. Griffith. 2012. Trends in Sediment-Related Water Quality After a Decade of Forest Management Implementing an Aquatic Habitat Conservation Plan. Technical Report, Humboldt Redwood Co., Scotia, CA 187 pp.

Water quality monitoring at 22 gaging stations in the Elk River and Freshwater Creek in north coastal California from 2003 to 2012 assessed effects of timber harvest and associated roads on turbidity and sediment yields. This study

did not find a linkage between decade-old timber harvest rates and erosion as did a previous study with just one year of data (Klein et al., 2012). Nor did this study find that road density was a significant factor in predicting erosion. The authors attribute the lack of a significant road response to the fact that many roads have been recently “stormproofed” so that a factor of ‘road density’ does not accurately reflect the reduced erosion potential of treated roads. Highest erosion rates were observed on lands underlain by the Wildcat Formation, a soft sedimentary rock.

Surfleet, C.G. 2007. Watershed analysis results for Mendocino Redwood Company Lands in Coastal Mendocino and Sonoma Counties. P.121-132 in Proceedings of the Redwood Region Forest Science Symposium: What Does the Future Hold? R.B. Standiford, G.A. Giusti, Y. Valachovic, W.J. Zielinski, and M.J. Furniss, eds. USDA Forest Service PSW-GTR-194.

TCRCD (Trinity County Resource Conservation District). 1998. The Grass Valley Creek Watershed Restoration Project: Restoration in Decomposed Granite Soils. Weaverville, CA. 163 p.

This summarizes restoration efforts to control the delivery of sand and gravel derived from decomposed granite soils in the Trinity River basin, California.

Thomas, R.B. and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. *Water Resources Research*. 34(12):3393-3403.

The authors reexamine a data set from a study by Jones and Grant (1996) which showed an increase in peak flows associated with roads. Thomas and Megahan used a different statistical technique to come to the conclusion that the previous study’s results could not be substantiated.

University of California Cooperative Extension: Forest Research and Outreach.

Website has links to information on forest road design, maintenance and improvement.
http://ucanr.edu/sites/forestry/Forest_Roads/

University of California Cooperative Extension, in cooperation with Northern California Society of American Foresters, Lahontan Water Quality Control Board, Tahoe Regional Planning Agency, California State Parks Department and US Forest Service, Lake Tahoe Basin Management Unit. 2013. Presentations from a workshop: Roads and Road Management in the Tahoe Basin.

http://ucanr.edu/sites/forestry/Workshops/Roads_and_Road_Management_in_the_Tahoe_Basin/

USDA Soil Conservation Service. 1992. Inventory of Sediment Sources, Grass Valley Watershed, February, 1992. Weaverville, CA. 381 pp.

Sediment sources include surface erosion on roads, stream crossing failures, and streambank erosion.

USDA Forest Service. 1999. Roads Analysis: Informing Decision about Managing the National Forest Transportation System. Misc. Rep. FS-643. Washington, D.C. 222p.

A roads analysis documents the benefits and risks posed by national forest roads. Managers need to balance between the benefits of access to national forests and the costs of road-associated effects of ecosystem values, including water

quantity and quality. This publication outlines a procedure to conduct such analyses. It includes a link to an annotated bibliography of 427 references on water-road interactions: www.stream.fs.fed.us/water-road

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(6) 1195-1207.

Detailed surveys of road drainage were conducted in two basins in the western Cascades of Oregon. The surveys revealed two major hydrologic flow paths that link roads to stream channels: roadside ditches draining to streams (35 percent of the 436 culverts examined), and roadside ditches draining to culverts with gullies incised below their outlets (23 percent of culverts). Gully incision is significantly more likely below culverts on steep (< 40 percent) slopes with longer than average contributing ditch length. Fifty-seven percent of the surveyed road length is connected to the stream network by these surface flowpaths, increasing drainage density by 21 to 50 percent, depending on which road segments are assumed to be connected to streams. This may alter flow-routing efficiency through extensions to the drainage network.

Wildlands CPR. 2012. Road Reclamation: Measuring Success. Missoula, MT.
(<http://www.wildearthguardiansresources.org/?q=resources/graip-report-fact-sheet>)

This report consolidates ongoing research from the Forest Service Rocky Mountain Research Station using the Geomorphic Roads Assessment and Inventory Package (GRAIP). The researchers used GRAIP to monitor the effectiveness of road decommissioning and storm-proofing projects implemented through the Forest Service Legacy Roads and Trails program in six western states. The report also summarizes how the Research Station is using GRAIP to conduct watershed assessments to identify the most problematic road/sediment problems. Based on their comprehensive ground-based assessments in four different watersheds, they have found that 90% of the sediment delivery is typically caused by less than 10% of the road system. Land managers concerned with sediment production can use the GRAIP analysis to prioritize road mitigation treatments to reduce sedimentation, thus reducing mitigation costs while increasing mitigation effectiveness.

Wohlgemuth, P.M. 2003. Post-fire erosion control research on the San Dimas Experimental Forest: past and present. In K.G. Renard, S.A. McElroy, W.J. Gburek, et al., eds. Proceedings: First Interagency Conference on Research in the Watersheds. Washington, D.C. U.S. Department of Agriculture. Agricultural Research Service: 645-650.

Zinny, C. 2008. Staff Report: Scientific Literature Review of Forest Management Effects on Riparian Function for Anadromous Salmonids. State Board of Forestry and Fire Protection. Sacramento, CA. 12 p. plus 7 appendices.

The report summarizes literature focusing on five aspects of riparian exchange functions: Biotic and nutrients, large wood, heat, sediment and water. Roads can have significant hydrologic impacts on a road segment scale by intercepting subsurface flow and altering hydrologic pathways. However, at the basin scale, paired watershed studies have not shown strong evidence to support road-induced increase in peak flow.