Forest Road Erosion Research at the Coweeta Hydrologic Laboratory

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The Coweeta Hydrologic Laboratory, Southern Research Station, USDA Forest Service, has been conducting basic and applied research addressing erosion and sedimentation from forest roads for over seventy years. This research has resulted in development of local, state and federal forest road construction standards, development and application of forest road bioengineering and National Forest System road best management practices (BMPs). Our most recent research has documented the effects of large-scale forest road reconstruction and BMP implementation on erosion rates, stream sedimentation and water quality in the southern Appalachian Mountains. Currently, we are developing and validating three methods to differentiate between natural and anthropogenic sediments in streams. These methods allow us to accurately quantify the direct impacts of forest roads on stream sediment budgets, sediment residence time and sediment transport rates.

Keywords: *Roads, road management, sedimentation, erosion control, best management practices, forest practices, watershed management, water pollution*

Introduction

The Coweeta Hydrologic Laboratory in Otto, North Carolina, is a research work unit of the USDA Forest Service, Southern Research Station (Figure 1). Coweeta was established in 1934 as an experimental forested watershed. The research mission focused on investigating the impacts of watershed management activities on water yield and water quality and expanding our knowledge and basic understanding of forest watershed hydrology.

The scientists and engineers who worked at Coweeta in the early years recognized that erosion and sedimentation from gravel roads was a major threat to forestry operations, water quality and water supply, aquatic ecosystems, hydrologic and hydraulic infrastructure. Consequently, scientists at the Coweeta Hydrologic Laboratory have conducted a wealth of research addressing the impacts of forest road construction, forest best management practices, road use, and road maintenance practices on hydrology, water quality and road longevity since 1934. Sun et al. (2004), Jackson et al. (2004) and Swift (1988) have previously summarized much of the history of forest road research conducted at Coweeta. In this paper, we provide an overview of these earlier works to set the historical context for a subsequent review of our contemporary forest road research.

Historical Forest Road Research of the Coweeta Hydrologic Laboratory

When the Coweeta Hydrologic Laboratory was established in 1934, engineers at the time recognized that erosion of forest roads was a serious problem (Figure 2). Road erosion reduced road life, increased maintenance expenses, damaged vehicles and harmed the aquatic environments. Some of the earliest research studies were conducted by C. R. Hursh, who recognized the inherent erodibility of cut and fill slopes and employed what we now call bioengineering to stabilize roadways (Figure 3). Significant reductions in soil loss from forest roads were accomplished by mulching or vegetating the adjacent cut and fill slopes (Hursh 1935, 1939, 1942). Project specifics including an evaluation of different plant types and bioengineering methods are summarized by Swift (1988). While improving and facilitating the construction

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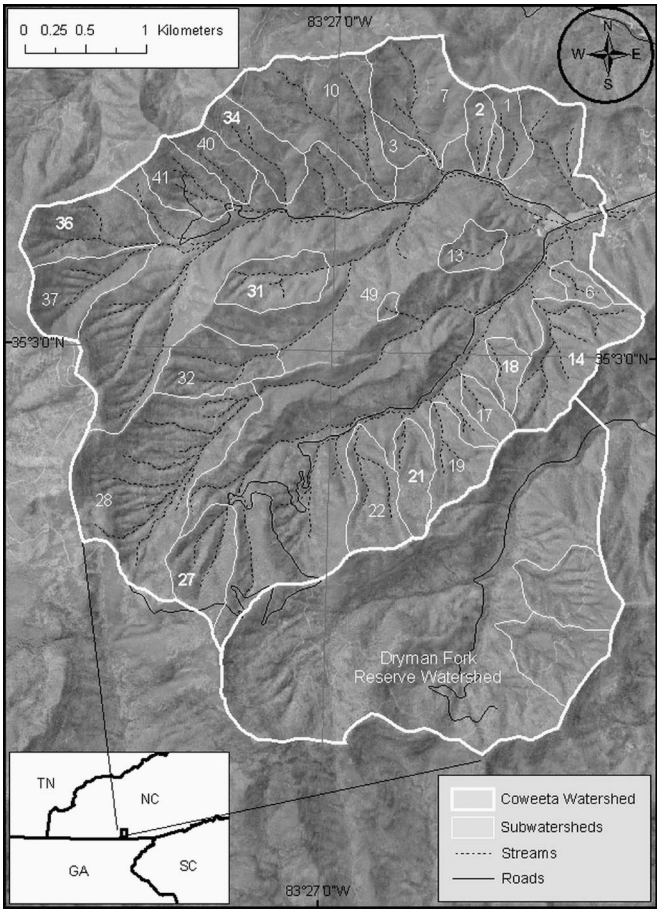
Figure 1: Coweeta Hydrologic Laboratory and its Experimental Watersheds.



of roads was a major motivation for this research, Hursh laid the foundation for subsequent research that specifically addressed the impacts of roads on stream water quality.

In 1942, a research demonstration project was initiated on Watershed 10 (Figure 1) to scientifically document the impacts of mountain logging practices on water quality. Typical logging practices, such as using ephemeral channels and riparian areas for skid trails (Figure 4), generated 408 m^3 of soil loss per km of road constructed (Lieberman and Hoover 1948a). Sediment delivery to streams was high and total suspended solids peaked at 5700 ppm (Lieberman and Hoover 1948b). Road erosion was so severe that downstream fish populations were significantly reduced (Tebo 1955), the roads became unusable and were decommissioned (Swift 1988).

Progressing from lessons learned in the exploitive logging experiment, Coweeta scientists conducted forest harvesting experiments to demonstrate how sound road building and watershed management practices accommodate water quality preservation and timber harvesting. Two watersheds were contracted for harvesting in 1955: Watershed 40 was to be harvested while managing for preservation of water quality and the adjacent Watershed 41 was harvested to

Figure 2: Erosion of an old logging road (photo by C.R. Hursh).

Figure 3: Example of early bioengineering to stabilize a cut slope road embankment (photo by C.R. Hursh).

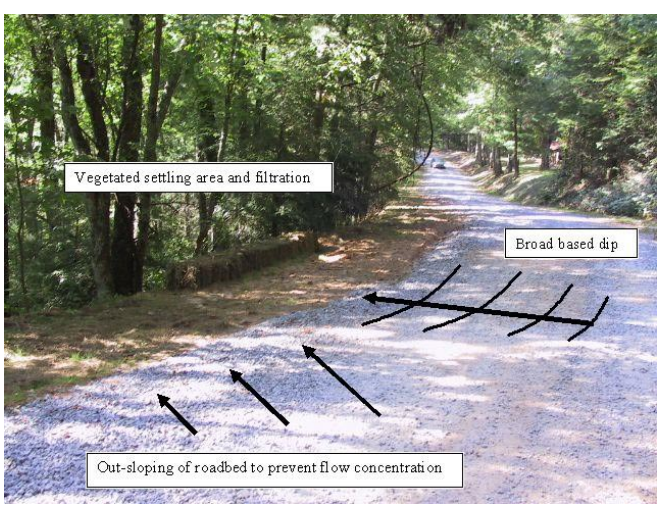
Figure 4: Skidding logs in the riparian area during an early logging experiment at the Coweeta Hydrologic Laboratory (photo source unknown).

facilitate timber extraction. Road construction practices on Watershed 40 were tightly controlled. Swift (1988) provides a discussion of specifics including road placement, width, engineering and vegetative methods. The implemented construction practices included contour roads, skidding logs away from streams and preventing stream disturbance. While these techniques protected water quality, they were deemed impractical by potential users because of perceived implementation and management costs (Swift 1988).

The Stamp Creek Demonstration Project in northeastern Georgia addressed the perceived cost limitations of adopting improved road designs and best management practices (Black and Clark 1958). From 1956 to 1960, forest harvesting was conducted on the Stamp Creek watershed with consultation on road design from Coweeta Hydrologic Laboratory scientists. Road maintenance and construction techniques employed were economically feasible because the roads were specifically designed to require minimal maintenance. Road quality and timber access improved, facilitating forest harvesting operations while minimizing impacts on water quality (Swift 1988).

These, along with other sustainable forest road construction practices, were employed in the multiple resource watershed management experiment in 1962. This experiment on Watershed 28 applied the multiple-use management concept that provides simultaneous benefits of forest products, fisheries and wildlife, and recreation needs while enhancing water yield and preserving water quality for municipal needs. New road building techniques such as out-sloping and broad based dips (Figure 5) were used to replace center crowned roadbeds, water bars, ditches and culverts to drain runoff. Hewlett and Douglass (1968) described these road engineering methods that further reduced road runoff and erosion. The experiment was so successful that the road building methods were adopted as standards for forest road construction by the national forests in Region 8 (the Southern Region) of the USDA Forest Service (Swift 1988).

Figure 5: Example of a properly constructed broad based dip from the Conasauga River Large-Scale Watershed Restoration Project, Cohutta Ranger District, Chattahoochee National Forest, USDA Forest Service (photo by M.S. Riedel).



Forest road research continued at Coweeta, striving for the goal of the "self maintaining road". Swift (1984a, 1984b) began a series of experiments to directly quantify where, when and how sediments were eroded from forest roads and to develop specific road engineering practices that would eliminate sediment sources. Swift and Burns (1999) and Swift (1988) have synthesized much of the knowledge about techniques learned from these comprehensive studies. Some of the most important findings include;

- Soil losses are greatest immediately after construction (Swift 1984a).
- Coarse gravel and grassing of roadbeds reduces erosion (Swift 1984a).
- Bare cut and fill slopes accounted for 70 to 80 percent of the total soil losses.
- Vegetating cut and fill slopes and graveling roadbeds reduced erosion to less than 10% of pre-treatment (Swift 1984b).
- The use of vegetated filter strips and brush barriers on fill slopes retains the majority of eroded sediments within the roadway (Swift 1985, 1986).
- 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 (Douglass and Swift 1977).
- Erosion and sedimentation from forest road stream crossings may affect the sediment budgets of streams for decades (Figure 6).
- Proper design of stream crossings, isolating roads from adjacent streams, and diverting road runoff onto the forest floor greatly reduce and may even prevent stream sedimentation (Douglass 1974; Swift 1985; Swift and Burns 1999).

Current Forest Road Research of the at Coweeta Hydrologic Laboratory

Current research of the Coweeta Hydrologic Laboratory represents a logical progression from the foundation of knowledge developed from the historical research. We have further advanced our ability to: (1) predict forest road erosion and sediment yield; (2) implement and evaluate effectiveness of forest road best management practices; and (3) quantify and understand stream channel sedimentation

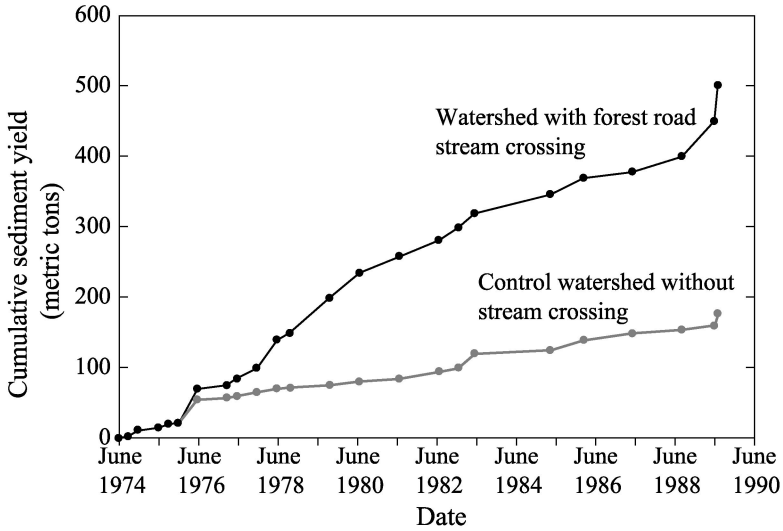


Figure 6: Cumulative sediment yield from a stream with road crossings as compared to a control watershed with no road crossings (adapted from Swank et al. 2000).

and sediment transport, sediment budgets and sediment cycling, and fluvial sediment dynamics.

Prediction of Erosion and Sediment Yield From Roads

The ability to accurately predict forest road erosion and sediment yield is crucial to preventing and mitigating stream sedimentation impacts. This is especially true with cumulative effects analysis when the long-term operation of hundreds of miles of forest roads across all landscape scales represents a large and chronic sediment source.

L.W. Swift developed a spatially explicit sediment transport model for the southern Appalachians (EPA 2000) that was incorporated into a spatially explicit GIS based soil erosion model (McNulty et al. 1995; McNulty and Sun 1998). Greenfield et al. (2001) further developed the model, incorporated empirically based sediment routing functions and the ability to estimate average annual stream sediment yields. This model, the "Sediment Tool", was incorporated into the U.S. Environmental Protection Agency's Watershed Characterization System (WCS) (EPA 2000). The Sediment Tool is a spatially explicit, GIS based, finite element, lumped parameter model which generates estimates of soil erosion, sediment routing and sediment yield. While this model is used for TMDL analysis and development, it had never been validated for such an application.

Riedel and Vose (2002a) customized data and data structure for WCS and the "Sediment Tool" to incorporate National Forest System roads, forest road management practices, and the highest quality terrain data in the remote mountains of the Chattahoochee National Forest in northern Georgia. They monitored road erosion and sediment yield from a wide variety of unpaved roads in the region. While they were able to qualitatively calibrate the model to observed data, they found model sensitivity to road characteristics was limited by the governing equations within the model and the resolution of the input digital elevation models. Simulated roadbed erosion and sediment yields were biased and did not agree with observed data.

Riedel and Vose (2003) subsequently monitored road erosion and sediment yield on a subset of the road sites after reconstruction and implementation of forest road best management practices (BMPs). The Sediment Tool did not accurately predict road erosion, sediment yield and BMP performance. Riedel and Vose concluded such application was beyond the capabilities of the model and that it should be better suited to larger scale applications such as land cover change analyses. Bolstad et al. (2006) have further validated the model on a larger scale across five watersheds in the southern Appalachian Mountains. These watersheds include two forested controls, a watershed with mountain home development impacts, another affected by valley agricultural practices, and one with mixed land use.

Implementation and Effectiveness of Forest Road Best Management Practices

Forest road research at Coweeta has long addressed the reduction of road erodibility, road sediment yield and stream sedimentation through the development of forest road BMPs. Clinton and Vose (2002) conducted one of the first comprehensive studies investigating forest road erosion that included paving as a BMP. While paving logically reduces the erodibility of forest roads, threats from potential impacts on stream sedimentation and the delivery of total petroleum hydrocarbons (TPH) were documented for the first time. As expected, the paved road system generated the least sediment, aggregate base gravel roads generated more and the unimproved road

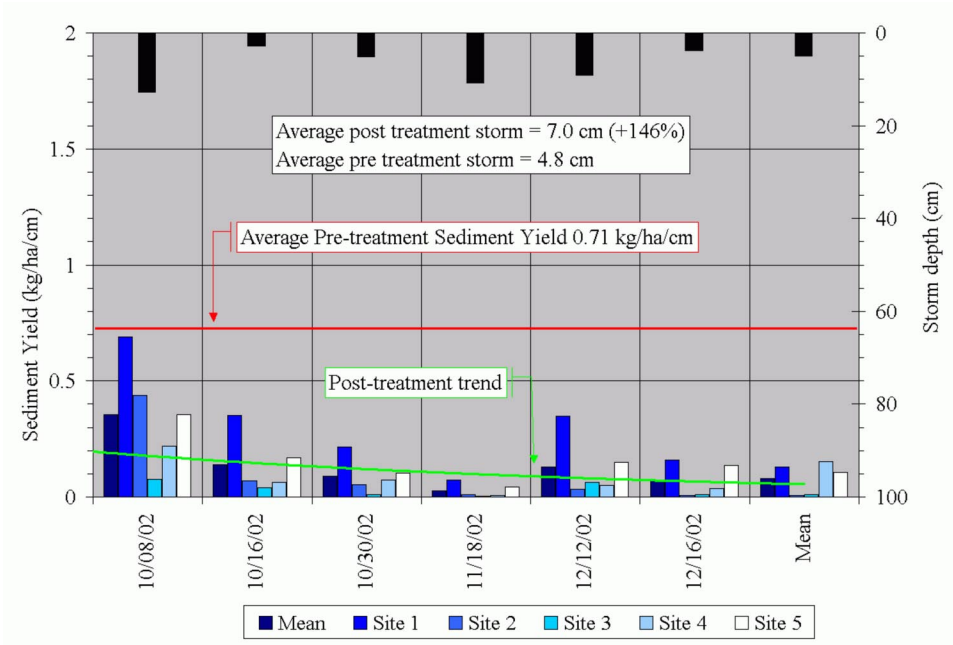


Figure 7: Comparison of pre and post-treatment sediment yield following reconstruction of a forest road with best management practices in the Conasauga River Large-Scale Watershed Restoration Project, Cohutta Ranger District, Chattahoochee National Forest, USDA Forest Service (Riedel and Vose 2003).

generated the greatest amount of sediment. The distances of sediment transport away from the road bed were, in order of decreasing distance, paved, improved gravel, improved gravel with sediment control and unimproved gravel. While TPH were found in runoff water at the edge of newly paved roads, the concentrations were extremely low. No TPH were found in collected runoff below the road, nor in stream water or stream bottom sediments, suggesting that TPH sorbed to sediments before reaching the streams. Clinton and Vose found gravel roads with failed BMPs (due to improper installation, lack of maintenance, or both) provided little, if any reduction in sediment yield as compared to gravel roads with without BMPs.

Riedel and Vose (2003) monitored sediment yield and transport in the Chattahoochee National Forest beginning in autumn 2001. During the summer of 2002, road reconstruction and installation of BMPs were completed along more than 20 miles (32 km) of forest roads (Figure 5). Sediment yield from these roads was monitored through autumn 2002. Despite a 46% increase in rainfall from the pre- to post-treatment period, road reconstruction reduced average sediment yield by 70% (Figure 7) (Riedel and Vose 2003). Specific examples of the road reconstruction and BMP implementation are reported by Riedel and Vose (2003).

Stream Channel Sedimentation and Sediment Transport

The transport of sediments sourced from gravel roads as bedload, despite the potential implications for aquatic ecosystems, has historically received very little research attention. Riedel et al. (2003), having previously identified road sediments deposited in the streambed and noticing ecological impacts (Riedel and Leigh 2004), initiated a pilot streambed mobility study. Several transects of scour and deposition pins were installed along a study reach, immediately adjacent to an unpaved gravel road (Figure 8). The stream scoured up to 10 cm of sand from its bed, exposing buried riffles and partially clearing pools of sediment (Figure 9). The sand and fine gravel in this stream were very dynamic. In-stream scour and deposition occurred frequently. No in-stream deposition occurred during small events, when road runoff was negligible. During larger events, road runoff and in-stream sediment deposition occurred. These results indicate that the implementation of forest road BMPs facilitates stream restoration, because mountain streams are capable of clearing the road sediments from their substrate if external sediment sources are eliminated.

Sediment Budgets and Sediment Cycling

Riedel and Leigh (2004) and Riedel et al. (2003) investigated methods of differentiating between natural and road derived sediments in stream channels. Van Lear et al. (1995) reported roads account for 85% of the potential sediment supply for streams in this region; however, no studies have attempted to directly validate this. Sediment samples from roads, native geology, soils and streambeds were gathered from a watershed in northern Georgia and numerous experimental watersheds at the Coweeta Hydrologic Laboratory. The samples were analyzed for total elemental composition using a triple acid digest. This allowed for the differentiation between geologically old,

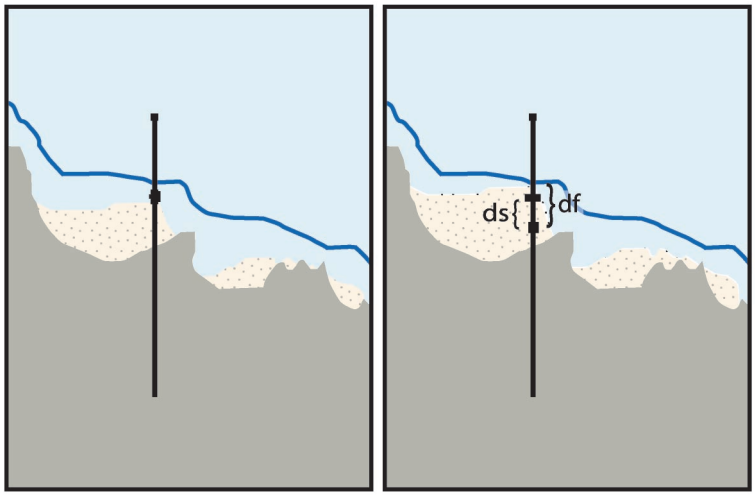
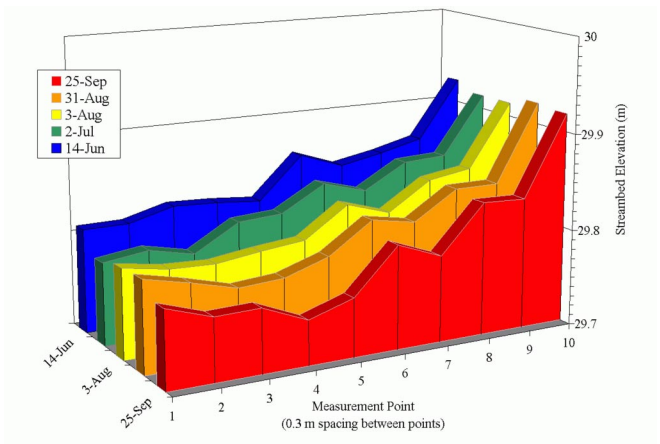


Figure 8: Conceptual diagram of scour and deposition pins installed in a stream channel. A loose washer is placed on each pin before installation. The elevations of the washers resting on the sediment surface are measured. Following a storm event, the depths of sediment on the washers and the distances the washers have fallen are measured to reveal streambed scour (ds), streambed deposition (df) and net streambed change (df-ds) during the storm event.

Figure 9: Net scour of a streambed cross-section over a 3½-month period (Riedel and Leigh 2004).



native sources of coarse streambed sediments (sand-size and finer) and fresh quarry-sources of streambed sediment such as road aggregate. Elevated sodium and strontium were clear indicators of road sediments and in-channel sedimentation from excessive road sediments. At these study sites, 50 to 75% of stream sediments finer than 2 mm were sourced from roads (Riedel and Leigh 2004).

Fluvial Sediment Dynamics

Riedel and Vose (2002b) monitored streamflow and water quality in mountain streams of northeastern Georgia to determine the impacts of gravel roads on suspended sediment budgets. An EPA benchmark stream with minimal sediment impacts served as a reference with which to compare results from three other mountain streams. Total suspended solids (TSS) concentrations were not representative of suspended sediment because the organic and mineral components of TSS were highly variable between streams. Excessive loading of suspended mineral sediment was linked to gravel roads adjacent to the affected streams. Mineral sediment loading was highest in autumn during peak road use for recreational and hunting activities. They concluded TSS could not be reliably used for the establishment of Total Maximum Daily Loads (TMDLs) for forested streams, because it did not differentiate between the suspended organic matter derived from naturally occurring allochthonous inputs versus mineral sediments from development and roads.

With additional monitoring, Riedel et al. (2003) determined that during larger storm events, road runoff and in-stream sediment deposition occurred. The two undisturbed forest streams showed no sedimentation impact because they were sediment supply limited, whereas the two streams with road impacts experienced sedimentation because sediment supply exceeded transport capacity. The authors hypothesized that the most significant impact of roads on aquatic ecosystems in this region was from streambed sedimentation. Consequently, TSS based TMDLs may not address the causes of sediment impairment of aquatic ecosystems.

In subsequent work, Riedel et al. (2004) determined that water quality parameters on these streams varied significantly on a seasonal and storm event basis. TSS

data on the benchmark stream and a forested stream exhibited strong hysteresis (lag between effect and cause), were elevated on the rising limbs of hydrographs, and declined rapidly on the recession limbs—further evidence of sediment supply limitations. While there was weak hysteresis apparent in the constituent concentrations and loadings of the impaired streams, it was not statistically significant. They developed a "hydrograph threshold" approach to constructing sediment rating curves that facilitated the development of sediment based TMDLs that directly linked loading rates to discharge frequency and duration relationships.

Summary

The impacts of forest harvesting on sediment yield are directly related to skid trail layout and road building and maintenance activities associated with gaining forest access and removing timber from the woods. When roads and skid trails associated with forest harvesting are properly constructed and maintained, forest harvesting generally has a minimal impact on stream sedimentation. Conversely, poor logging practices and the incorrect design and maintenance of forest roads cause significant stream sedimentation. Many of the historical and often ill-conceived methods of forest road construction and maintenance caused large increases in forest soil erosion and stream sedimentation. Based on decades of research to improve road construction and maintenance, numerous practices that minimize erosion and sedimentation have been identified. Examples of these practices are coarser paving gravels, grassed roadbeds, the construction of broad based dips, brush sediment barriers along road margins and road buffer strips.

Sedimentation of streambeds may also be prevented by the proper use and maintenance of forest road best management practices. Indeed, in steep mountain streams, forest road reconstruction and adoption of BMPs may facilitate stream restoration because the reduction of road sediment yield allows streams to flush themselves of previously deposited road sand and fine gravel. Historical and current research suggests the long held ideal of a "self-maintaining" forest road may nearly be attainable.

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