Evaluating the Effects of Sedimentation from Forest Roads: A Review

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Abstract

Forest roads are generally unpaved roads that provide access throughout the forested environment for commercial and recreational purposes. Without proper design and construction, sediment from the road surface may dislodge due to precipitation or vehicular use and travel to nearby water bodies in stormwater runoff. In recent years, the U.S. Environmental Protection Agency considered addressing stormwater discharges from forest roads through regulations under the Clean Water Act. The purpose of this literature review is to evaluate the sediment production and transport from forest roads, water quality impacts caused by sediment, and to illustrate how to minimize impacts without additional regulations. The research reviewed emphasized that forest roads are the greatest potential source of sediment in the forested environment, however, the voluntary use of best management practices can significantly limit sedimentation and its associated impacts to water quality and aquatic health.

1 Introduction

The U.S. Forest Service (USFS) defines logging, or silviculture as it is also known, as the "art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs of society."[1] Silvicultural activities include thinning, harvesting, planting, pruning, burning, site preparation, and forest road construction. Forest roads are built to provide access for silviculturalists throughout forested systems. These roads are generally unpaved and are considered the greatest potential source of sediment pollution from silvicultural activities (Fulton and West 2002).

To reduce the impacts of forest roads on nearby water bodies, landowners, private companies, and public entities implement best management practices (BMPs) that reduce and treat the sediment-laden runoff that flows from forest roads. The primary objectives of this paper are to evaluate the impacts of forest road design, construction, use, and management on erosion; determine how sedimentation

[1] https://www.fs.fed.us/forestmanagement/vegetation-management/silviculture/index.shtml

generated from forest road activities affects water quality; and identify practices to reduce the impacts of forest roads on water quality. In doing so, we must understand the following:

- What are forest roads?
- How are forest roads regulated?
- How is sediment produced from forest roads?
- How are forest roads hydrologically connected to water bodies?
- How do forest roads affect stream health?
- What BMPs mitigate the effects of forest roads?

2 Forest Roads

Forest roads are essential components of the human use of forested systems. These roads are found in forests all over the U.S. and provide important access for a wide range of activities including silvicultural operations, recreation, fire protection, and transportation. Without roads, development of the economic activities derived from forests would be difficult. Today's network of forest roads was constructed over many years and includes both active and inactive roads that vary in age and condition.

In addition to publicly-owned roads that are maintained by federal, state, or local governments for public use, private forest land owners invest considerable resources in forest road construction and maintenance. Private forest land owners include a vast spectrum of people. A family in Virginia may own 100 acres of harvestable forest land compared to the Weyerhaeuser Company, the largest private sector owner of softwood timberland in the U.S. and Canada[2], that owns millions of acres of forest land. Private forest land owners view their private roads as critical assets that enhance property values, maintain economic viability, and facilitate sustainable management of forest resources.

[2] http://forisk.com/blog/2016/05/02/forisk-forecast-tracking-the-top-timberland-owners-and-managers-in-the-u-s-and-canada-2016-update/

Forested ecosystems, where forest roads are constructed, consist of large areas of vegetated cover and soil with high infiltration capacities, resulting in minimal surface runoff even during large storms (Stednick 2008). Some of the best quality fresh water sources in the world are in forested ecosystems (Neary et al. 2009). Forests can be harvested sustainably for timber if managed properly, although some degree of physical, biological, and ecological impairment is an inevitable consequence of silvicultural operations. The most predominant impairments come from forest roads used in silviculture operations (Murphy and Miller 1997). Even when well-located and carefully designed, adverse water quality impacts can result from forest roads if they are not properly operated and maintained.

Although the impacts of forest roads are widespread, the severity of the resulting impairments varies between locations. The spatial variability of impairments results from varying soil characteristics, average annual precipitation, established vegetation, and prior land management (EPA 2005). The variations in rates of erosion, sediment delivery, and the intensity of forestry activities (as measured by road density and traffic levels) also lead to vastly different impacts in different locations and watersheds. Temporal variability also arises with impacts from forest roads. Roads built fifty years ago were not built to the higher standards of today, thus making them more likely to impact streams (EPA 2005).

2.1 Legacy Roads

Legacy roads are relevant because, to some degree, the water quality impairments from forest roads are a consequence of past forestry practices and activities. In some states, such as Connecticut and New Mexico, BMP regulations have changed greatly within a single decade. In other states, including Idaho and Washington, forest practice rules are almost continuously evolving. Changes in logging systems, reforestation techniques, and environmental protection requirements have meant that the concepts of forest best management practices are always evolving (Keller and Sherar 2003).

The USFS Legacy Roads and Trail Remediation program[3] was established in 2008 to focus work efforts on forest roads that urgently needed decommissioning, repair and maintenance, and fish passage

[3] https://www.fs.fed.us/restoration/Legacy_Roads_and_Trails/

barrier removal. Prioritization is given to USFS road segments that have the greatest potential to adversely impact water quality in water bodies that support threatened, endangered, and sensitive species or community water sources. From 2008 to 2012, the program provided approximately $300 million to road and trail restoration efforts across the national forest system. By repairing, restoring, and decommissioning older roads, the USFS is ensuring the stability of legacy roadways and greatly reducing the likelihood environmental impacts from these roads.

2.2 How EPA Regulates Silviculture through the Clean Water Act

Silviculture is considered under the Clean Water Act (CWA) as both a point and nonpoint source. The EPA[4] defines the term "nonpoint source" as "any source of water pollution that does not meet the legal definition of 'point source'." In section 502(14) of the CWA, the term "point source" means "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture."

40 CFR Section 122.27 states that silvicultural point sources include any discernible, confined and discrete conveyance related to rock crushing, gravel washing, log sorting, or log storage facilities which are operated in connection with silvicultural activities and from which pollutants are discharged into waters of the U.S.[5] Section 402 of the CWA requires permits for these discharges under the National Pollutant Discharge Elimination System (NPDES) permit program. NPDES permits are designed to protect water quality by setting limits on the amount of pollutants that are discharged to a water body.

Nonpoint sources from silvicultural activities include nursery operations, site preparation, reforestation and subsequent cultural treatment, thinning, prescribed burning, pest and fire control, harvesting operations, surface drainage, or road construction and maintenance (EPA 2005). Oversight of

[4] https://www.epa.gov/nps/what-nonpoint-source
[5] https://www.law.cornell.edu/cfr/text/40/122.27

nonpoint pollution is primarily delegated to the states through Sections 208 and 319 of the CWA. Section 208 of the CWA requires all states to identify nonpoint sources of pollution, their cumulative effects, and methods of controlling them. Federal funding, designated by Section 319 of the CWA, provides financial support for state and local nonpoint source efforts. Under this program, grant money is given to states, territories, and tribes to support demonstration projects, financial assistance, public education, technical assistance, technology transfer, training, and monitoring programs that assess specific nonpoint source implementation projects.

As previously mentioned, road construction and maintenance relating to silvicultural activities are considered nonpoint sources. In *Environmental Defense Center, Inc.* v. *U.S. EPA* (9th Cir. 2003), environmental groups argued that forest roads are point sources because they contain ditches which act as a discernible, confined and discrete conveyance of polluted stormwater to waters of the U.S., and therefore should be permitted under the NPDES program. The construction of paved roads (when the project site disturbs more than one acre) and roads that are part of a municipal separate storm sewer system are already regulated under the NPDES program. In 2012 and 2016, EPA concluded that they will not regulate logging roads and forest roads, respectively, under the NPDES permitting program. EPA recognized the success of voluntary BMP programs that protect water quality from forest road runoff and decided to encourage the implementation of these existing efforts rather than develop additional regulations.

3 Erosional Processes from Forest Roads

In undisturbed forests, erosional energy from raindrops is dissipated by the tree canopy and the forest floor detritus, which shield the soil from direct exposure (Douglass 1975). Overland flow and concentrated flow energy effects in undisturbed forests are mitigated by the organic matter and upper soil horizons, which accumulate water and drain slowly, allowing greater infiltration and reducing the detachment and transport of soil particles. If the forest floor is not removed or heavily disturbed, it effectively protects soil from splash erosion, reduces overland flow velocities, and promotes infiltration of water into the underlying soil.

After the soil has become fully saturated during precipitation events or compacted from road construction, infiltration ceases and water begins to move overland in sheet and/or concentrated flows. The kinetic energy and erosion potential of moving water are determined mostly by velocity and flow depth, which are influenced by total rainfall or snowmelt, topography, and the rate of runoff. Particle size, density, and shape influence their movement in flowing water. Smaller, lighter particles such as clays and fine silts are mobilized quicker and stay in suspension longer than the heavier sands and gravels. Bilby (1985) found that most of the sediment delivered to streams from the road surface was very fine, clay-sized particles. Bloser and Scheetz (2012) identified a significant “first flush” effect on the road segments subject to their rainfall simulation studies. The ‘first flush’ concept states that most sediment pollution is generated at the beginning of the precipitation event. As the event continues, the easily detached sediment is washed away, and the remaining material will be more resistant to erosion. The amount of sediment removed during the ‘first flush’ will depend on the type of soil properties and how compacted the road surface is during the precipitation event.

Researchers have studied the erosional processes associated with forest roads extensively, and the concepts are relatively well understood. Where roads expose mineral soils to raindrop impact and reduce the infiltration capacities of forest soils, surface runoff and erosion may occur where formerly these mechanisms were absent (Stednick 2008). If the presence of a road reduces the inherent stability of a slope (i.e., by removing vegetative cover, intercepting and channelizing near-surface groundwater, etc.), this may increase the frequency and magnitude of landslides or other types of mass soil movements. Stormwater runoff from the road may also increase the magnitude and frequency of peak flows thereby increasing the erosive potential of a stream and affecting its capacity to transport bed and bank materials.

3.1 Rill and Gully Erosion

While overland flow can dislodge and transport soil particles, most erosion occurs in areas of concentrated flow and mass wasting from steeper terrain. Water concentrated into ditches and channels presents greater risk for rill erosion and can more easily detach and transport sediment compared to overland flow. Ditches are more likely to erode if they have bare soil due to recent construction or maintenance (Elliot et al. 2009). Even if vegetated or otherwise stabilized, ditches can transport detached sediment from the road surface or cut banks above the ditch. Gully erosion may also contribute to the process in wheel depressions or ruts along the forest road surface. Rills and gullies on unsurfaced roads may concentrate surface flows, extend flow paths, and increase the amount of erosion from the forest road (Elliot et al. 2009). Where rills and gullies exist, the flow path of runoff carrying eroded sediment follows the gully or rut until a cross drain or grade change occurs (Elliot et al. 2009). Once the flow path is altered, runoff may then flow into a swale or ditch, along a berm, or across the forest floor.

Areas where flows converge (e.g., convex slopes, swales, ditches, channels) resist erosive forces if protected by vegetation, tree harvest slash debris, rolled erosion control products, rock, or stabilized by some other means. However, when soil is exposed in concentrated flow areas, rill and gully erosion typically follow. The rate of erosion is generally governed by the slope angle, length of slope, soil erosivity and erodibility, and any soil cover or management practices present. Chronic erosion from unsurfaced forest roads, cut and fill road slopes, and destabilized ditches is well documented (Bilby et al. 1989; Megahan and Kidd 1972; Reid and Dunne 1984), and is often the dominant source of road-related sediment input to streams.

3.2 Mass Movement of Soil (Landslides)

Mass movement of soil is aided by water and ice, but gravity is the primary transport mechanism. Mass movement can occur as shallow debris slides, deep-seated slumps, and rapid debris flows (Williams 1999). Sidle et al. (1985) found that mass movements of soil in forests were 30 to 300 times greater in watersheds with roads versus those without roads, due to the higher risk of gullying and mass soil movement from channelized runoff flows. Total sediment production from logging roads in an Idaho study (Megahan and Kidd 1972) was 770 times higher than in undisturbed areas, with about 71 percent of the increased sediment production attributed to mass erosion and 27 percent to surface erosion. McCashion and Rice (1983) investigated erosion due to forest roads and logging in northwestern California. Mass erosion was the predominant form of erosion occurring from the study sites. In steep watersheds, more sediment may originate from mass wasting, which tends to deliver greater quantities of sediment to the stream.

Landslides, debris flows, and other mass movement or wasting of soil are also significant in transporting sediment and making it available for loading into surface waters. These events result from the dislodgment and downslope transport of soil and rock material as a unit under direct gravitational stress. The slippage and movement of large and relatively cohesive volumes of soil downslope occurs naturally, but roads and road management practices can accelerate these processes (Sidle et al. 1985). The mass movement of soil from forest roads includes slow displacements such as creep and solifluction as well as rapid movements such as landslides, rock slides and falls, earthflows, debris flows, and avalanches. Water and ice can play an important role in the process by acting as the dislodging force that initiates and compounds the mass wasting. Rates of mass wasting vary greatly, depending on climatic, geologic, and topographic factors (NCASI 2001).

Road-related landslides can result in significant sediment impacts due to the volume of material in the failed fill, and by scouring headwater channels (Miller et al. 2005). Whereas other erosional processes occur on a more chronic basis, landslides tend to occur episodically and are often the result of large rainfall events. Landslides are typically the dominant erosion mechanism in areas with steep slopes and occur more frequently on poorly designed or poorly placed roads. Prior to mid-1980s, excavated soil and rock from full-bench road construction was side cast on very steep slopes below the road prism (FPAC 2001). These steep slopes were often associated with landslides and other rapid movements of soil and rock.

Ice et al. (2004) found that most landslides associated with managed forests came from road corridors and were often associated with specific practices, such as side cast road construction, poor location, and inadequate drainage. Where roads traverse unstable hillslope areas, such as inner gorges, swales, or breaks in the slope, landslide risk increases (Weaver et al. 1998). Research conducted in Washington (Reid 1981) and northern California (Hagans et al. 1986) found the likelihood of landslides increases in areas with roads in comparison to forest areas without roads.

3.3 Other Factors that Affect Road Erosion

Road location, including climatic region, plays another contributing factor that may influence road erosion. For example, in wetter regions with greater rainfall intensity and duration, surface erosion is more likely to occur (Grigal 2000). In colder regions where snow is the dominant form of precipitation, snowmelt runoff may contribute to the sediment loading that reaches downstream sources (Simon et al. 2006). In these regions, protecting the road surface with gravel or other stabilizing materials and limiting traffic use during wet conditions can reduce road erosion. Another factor contributing to road erosion is road age. Newly constructed roads can have up to 10 times more surface erosion than subsequent years due to loosened and unstable soil from construction (FPAC 2001; Swift 1988). Additionally, older roads that were not properly maintained or decommissioned can continue to erode over time.

Although most roads will have some effect on their watersheds, in any given forest or watershed a small percentage of road area (or length) is often responsible for most of the erosion. Roads that have improper design, layout, or construction will generally have erosion problems to a greater degree. Problems usually stem from steep grades, sharp curves, steep side-slopes, soft or erosive surface material, improper stream crossings, proximity to streams, and poor drainage (Lakel 2008). For example, in a study of road-related erosion, Rice and Lewis (1986) found only 0.6 percent of the road length had events displacing significant quantities (greater than 15 m^3, approximately two dump trucks) of eroded material.

4 Forest Road Design and Construction

Road construction is considered the largest potential source of sediment production during forest operations (Hornbeck and Reinhart 1964; Megahan 1980). Construction activities that expose or compact the soil can reduce infiltration and concentrate surface runoff thereby accelerating erosion. Soil losses are greatest during and immediately after road construction (destabilized road prism, disturbances by heavy equipment passage) (Swift 1984). However, water quality impacts can continue throughout the active lifetime of a road and even after road closure and decommissioning. The primary water quality effects associated with the existence of forest roads include sedimentation, elevated temperature from buffer removal and sediment deposition, and habitat degradation.

Forest roads are constructed in several different ways. Two common methods are cut and fill and full bench construction (Wilbrecht et al. 2000). Cut and fill involves excavating the back slope (also referred to as top or cut slope) and compacting this material below the traveled way as fill slope, as shown in Figure 1. Adequate compaction of fill slopes is essential to prevent erosion and maintain the integrity of the road. Additional material placed on the fill slope may ensure stability. Riedel et al. (2007) found cut and fills slopes left bare accounted for 70 to 80 percent of total soil loss and that vegetating these slopes can reduce erosion to less than 10 percent compared to no vegetation (Swift 1984).

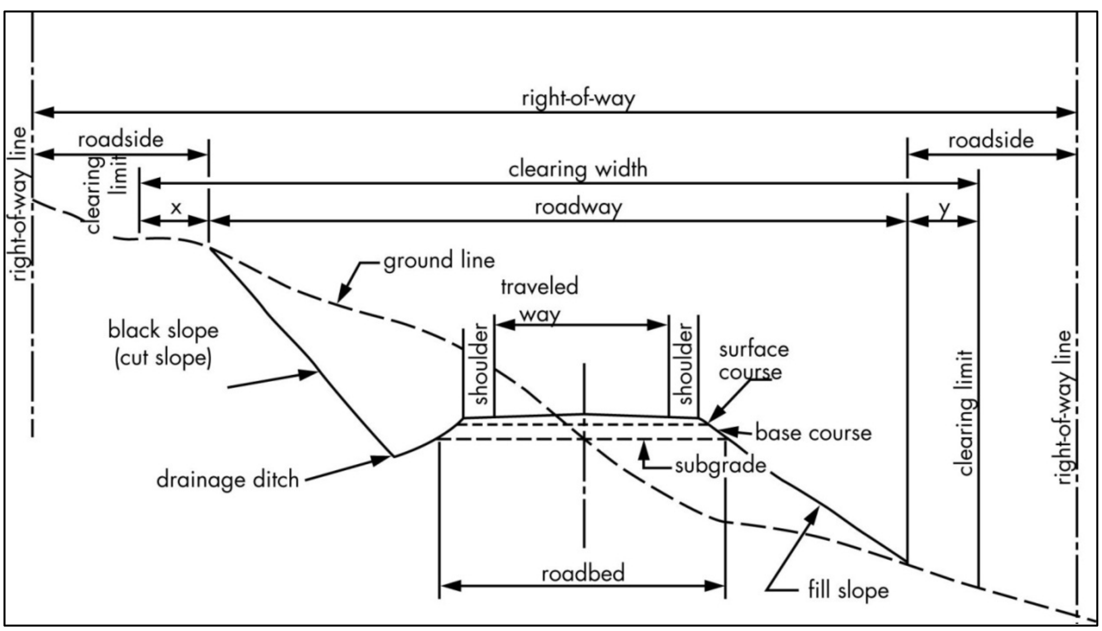

Figure 1. Cross-sectional diagram of a road (US Department of Interior 2007)

Full bench construction involves excavating a bench into the slope that is equal to the width of the traveled way, shoulders, and any required ditches. Instead of using the excavated material to form a fill slope, the waste material is usually hauled elsewhere. For any method of road construction, timing and location are very important factors to consider. Construction should occur during drier months to minimize erosion. Constructing forest roads near streams should be avoided whenever possible and a riparian buffer should be left between the road and stream to filter pollutants contained in road runoff. Steep slopes should be avoided whenever possible especially with cut and fill or when steams are downslope from the construction. In addition to the longitudinal slope of the road and its ditches, the lateral slope of the road and the general construction configuration also influences sediment generation and transport.

The cut slope is the soil surface area above the roadway where the back slope was excavated. Without proper stabilization, cut slopes can erode and deposit sediment on to the roadway. Elliot et al. (2009) found that cut slopes shorter than three meters primarily experienced interrill erosion while longer cut slopes experienced rill erosion. The authors also found that cut slopes located on steep terrain with seasons of high rainfall frequently experienced mass wasting which deposit sediment in road ditches or on the road surface. Overland or channelized flow then conveys the detached sediment down the roadway. Luce and Black (1999) found that cut slope height did not affect sediment production, rather vegetation and soil texture were the dominant factors. They concluded in their study that sediment production from aggregate covered roads on a silty clay loam was about nine times greater than that from roads constructed on a gravelly loam and road segments where vegetation was cleared from the cut slope and ditch produced about seven times as much as road segments where vegetation was retained. The results illustrate the importance of slope revegetation and ditch cleaning during maintenance.

Out sloped roads can experience rill erosion on the fill slope if the fill is not properly protected and stabilized with rock or a retaining structure (Elliot et al. 2009). However, constructing rolling dips or water bars to break up the flow path length of an out sloped road and reducing the slope of the fill can limit erosional impacts. These practices can allow runoff to disperse across a forested buffer or vegetated hillside as sheet flow, minimizing erosion (Elliot et al. 2009). Finally, ditch erosion can occur when roads are insloped and the ditch is not properly vegetated or stabilized. Figure 2 illustrates these various road configurations and potential flow paths runoff may take.

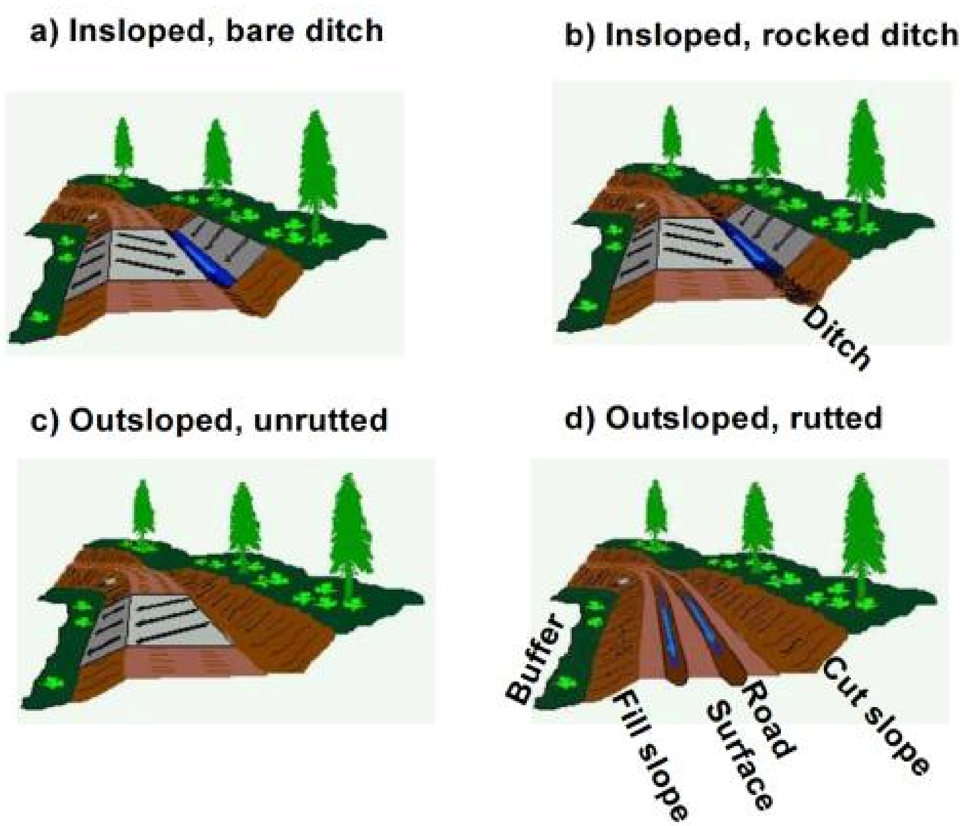

Figure 2. Insloped and outsloped forest road configurations (Elliot et al. 2009)

Bloser and Scheetz (2012) developed a report on the amount of sediment generated from unpaved roads in the Allegheny National Forest in Northwestern Pennsylvania. The study used a rainfall simulation device to determine the amount of sediment produced. Their results indicated that a single storm of similar intensity and duration to the design storm could be expected to produce over 1,100 tons of sediment from the unpaved roads and approximately 385 tons of that sediment could be expected to reach nearby streams during each storm. It is important to note that erosion rates are highly variable due to the natural variability in the factors that cause erosion. Even a well-designed erosion experiment frequently results in variations from the mean of up to 50 percent (GLEC 2008). Such a wide range of variability has caused skepticism among stakeholders and should be considered when evaluating erosion rates.

Primary forest roads that are heavily traveled are sometimes paved or surfaced with gravel or stone. Paving or surfacing roads can protect the road surface from erosion and reduce rut formation. However, paving the roadway can have deleterious effects such as more rapid runoff from the road surface that can increase flows and channel erosion in ditches and other areas adjacent to the road. The gravel surface may break down from heavy use and increase the amount of fine sediment on the road surface (Foltz and Truebe 2002), especially during wet periods (Reid and Dunne 1984). Bilby (1985) found that the broken-down gravel can even represent most fine particles eroded from the road surface.

5 Forest Road Traffic

Once constructed, forest roads receive varying levels of traffic that can have a significant effect on road erodibility (Elliot et al. 2009). Some forest roads are only used seasonally while others are used year-round and through all weather conditions. Heavy traffic can increase the development of ruts on the road surface, compact the surface aggregates into the subgrade, and as previously mentioned, break down the surface aggregates (Elliot et al. 2009). When this occurs, the hydrologic conductivity of the soil is decreased and the amount of runoff and erosion is increased. Road segments that receive more traffic are more compacted and exhibit higher structural strengths. Bloser and Scheetz (2012) found that when forest roads experience low traffic volumes, sediment production is heavily based on the road slope and width. However, when roads are heavily used, then slope and width are less important and road strength dictates the amount of sediment produced. The authors suggested adding vegetative cover to the road surface on roads that are only used seasonally or experience low traffic volumes to reduce sediment production.

Foltz (1996) and Luce and Black (2001) found that erosion rates on low traffic roads are 20 to 25 percent less than erosion rates on high traffic roads. In another study, MacDonald and Larsen (2009) measured sediment production rate from 2002 to 2006 in the Pike National Forest (approximately 65 km southwest of Denver) and determined that the mean annual sediment production was 42 Mg per hectare of road surface. In their study, MacDonald and Larsen (2009) reported a 10-fold variation in annual sediment production and attributed this variability primarily to the differences in rainfall erosivity and increase in traffic because of forest thinning operations. The authors reported that unpaved roads produce about 0.13 Mg per hectare of sediment per year. The season of road use also influences erosion rates. Traffic on unsurfaced or gravel-surfaced roads during wet periods can produce large quantities of fine-grained sediment that is easily transported in runoff (Reid and Dunne 1984).

6 Hydrologic Connectivity between Roads and Streams

Forest roads and their network of drainage ditches can continue to generate and convey sediment even when not under construction or in use. The exact nature of how sediment is generated, transported, and discharged to water bodies is based on a variety of factors including the condition of the road surface, construction configuration, maintenance practices, and measures taken for road decommissioning. These factors, individually or in tandem, are site-specific, and are in turn affected by topography, climate, soils, geology, and other parameters. The flow path followed by runoff is the key to understanding road erosion processes and thus water quality impacts from forest roads. Roads can convey stormwater runoff and sediment to nearby water bodies, if not properly designed and maintained. As mentioned previously, ruts and gullies along the road surface and ditches adjacent to the roadway extend the flow path of stormwater runoff and therefore increase the connectivity between forest roads and streams.

Connectivity between a road and stream describes the probability that runoff from a road, and the sediment it carries, will reach the stream network (Croke et al. 2005). Sediment is carried by runoff in either dispersive or advective (channelized) pathways (Takken et al. 2006). Advective pathways are generally associated with culvert pipes; dispersive pathways are associated with mitre drains and push outs. Advective flow has little opportunity to deposit finer-grained sediment, whereas dispersive pathways may provide conditions for deposition (Lane et al. 2006). Most fine, silt-sized sediment (i.e., 62.5 µm and smaller) is carried as wash load, and does not settle out of suspension until the water infiltrates the soil (Hairsine et al. 2002).

Dispersive flow is more likely to infiltrate before reaching a stream, as advective flow can travel two to three times further from the road prism prior to infiltration (Croke et al. 2005). Roads closer to streams are more likely to have higher connectivity because there is less distance for water to infiltrate and sediment to be deposited (Bilby et al. 1989; La Marche and Lettenmaier 2001). These processes are documented, but little is known about changes in sediment fluxes as runoff moves across the landscape to streams (Croke et al. 2005).

Roadside and relief ditches can maintain and even increase runoff flow velocities. When these ditches are hydrologically connected to surface waters, sediment discharge to the water body is likely. This happens because channelized flows generally have a high flow rate per unit width and are less likely to fully infiltrate before reaching a major channel (Elliot and Tysdal 1999). Channels themselves may also act as a source of sediment to the runoff flows, if not properly stabilized.

The literature clearly shows that roads result in sediment production and movement but it is often uncertain how much is delivered to streams. In the Ouachita Mountains of Arkansas, Miller et al. (1985) traced 70 percent of the total sediment delivered from a forestry operation back to roads. The distance between the forest road and a stream is of great importance when it comes to sediment delivery. Sediment produced by a roadway is far more likely to reach a water body if the roadway and associated ditches discharge directly to or near a stream. Areas where roads intersect drainage channels or streams (i.e., stream crossings) also greatly increase the connection between road and water body. Douglass and Swift (1977) concluded that nearly all the sediment yield increase to streams following harvest were attributed to stream crossings, even though stream crossings only represented one percent of the total watershed area and 17 percent of the total road length. Moreover, the sediment produced at forest road stream crossings is significant enough to impact the sediment inputs to a steam for decades (Riedel et al. 2007).

Forest road stream crossings are a major source of sediment to streams and contribute more sediment to streams than any other land management activity (Meehan 1991). Stream crossings have such a great potential to adversely impact water quality since there is no buffer space to settle sediment and filter runoff. In some instances, it is unavoidable to build a road across an existing stream channel. At these intersections, a stream crossing such as a bridge or culvert are installed perpendicular to the stream. When designed, or installed improperly, these crossings can experience severe erosion (Harris et al. 2008). When the stream crossing is inherently unstable, riprap is often placed to reduce the likelihood of the road fill eroding (Luce et al. 2001). Limiting stream crossings, constructing roads as far away from a stream as possible, and leaving a forested buffer between the road and stream will greatly reduce the hydrologic connectivity between a forest road and nearby streams.

A study in the Coast Range Mountains (Durgin et al. 1988) found that roads accounted for four percent of the land area but 76 percent of the measured erosion, with the most common sediment source listed as fill slopes immediately adjacent to watercourse crossings. Woods et al. (2007) found that the clear majority of sediment discharges to forested streams in western Montana came from only a few road drainage outfalls. Swank et al. (2001) found that cumulative sediment yields from a stream with road crossings far exceeded the yield in a control watershed with no road crossings.

7 Impacts of Forest Roads on Water Quality

The previous sections detailed how forest roads facilitate the processes of erosion and sedimentation and how the sediment produced makes its way to surface water bodies. The following sections explain the potential impacts these processes have on forest hydrology, stream flow, water quality, and aquatic life. As mentioned throughout, these impacts are highly variable and sometimes difficult to measure. The most severe impacts can occur when sediment loads are produced simultaneously or cumulate throughout a watershed (NCASI 2001).

7.1 Impacts on Forest Hydrology

Williams (1999) found that roads impact watershed integrity through three mechanisms: by intercepting, concentrating, and diverting water. Forest roads intercept rainfall that would otherwise infiltrate into the forest floor or be taken up by vegetation. The roads then concentrate the water to form a steady flow that is maintained either on the road surface itself or in ditches adjacent to the road. Diverting the water from its natural flow reduces groundwater recharge and uptake by vegetation and increases the potential for erosion. This unnatural flow follows the grade of the road and landscape and can discharge directly into a stream, if hydrologically connected. This process greatly affects the forest hydrology and can alter flow in the receiving stream and even erode channels. It is unclear to what extent these alterations occur.

7.2 Impacts on Stream Flow

Peak flow responses to silvicultural activities are highly variable and depend on many factors such as basin size, topography, elevation, and soil characteristics, including soil moisture storage (Jones and Grant 1996). Brown (2010) found that the severity of harvest disturbance and road density were two aspects of silvicultural activities that can increase peak flow, initial flow rate, storm flow volume, duration, and recession time. McFarlane (2001) concluded that road density and the stability of the soils beneath the roadway are two road-related factors that not only impact suspended sediment yield in a watershed, but can significantly contribute to changes in peak flows.

Gucinski et al. (2001) concluded that the effect of roads on peak flows is relatively modest and the associated issues of changing stability and predictability from roads may be of little importance to aquatic habitat suitability. Several other studies have shown similar results, that few changes in peak flows occur because of silvicultural activities, even clear-cutting (Harris 1977; Harr et al. 1982). This evidence suggests that changes in peak flows are not as important as were once thought, especially because the small to average peak flows, i.e., channel maintenance flows, not the larger channel forming flows, are most affected by forest roads and other silvicultural activities (Stednick 2008).

In a review of forest practices on peak flows and channel response for Western Oregon and Washington, Grant et al. (2008) found that despite the interest in channel response to peak flow increases, no field studies explicitly link peak flow increases with changes in channel morphology. The authors note that although there is extensive literature on forest harvest effects on stream channels, no studies demonstrate a direct correlation between peak flow changes attributed to forest harvest practices alone and changes to the physical structure of streams. Changes attributed to peak flow increases are likely to be less significant than other impacts associated with forest harvest activities such as landslides, debris flow, and surface erosion.

7.3 Turbidity and Suspended Sediment

The delivery of sediment to a stream causes the water to become turbid. Turbidity is a measure of water clarity based on how much light is scattered by the suspended sediment (solids) present in the water. High turbidity in a stream can increase water temperature because suspended sediment absorbs more heat. Higher water temperatures reduce the amount of dissolved oxygen in the water because warm water holds less dissolved oxygen than cold water. Since high turbidity reduces the amount of light penetrating the water, photosynthesis is also reduced, further reducing the production of dissolved oxygen.

Low dissolved oxygen, reduced photosynthesis, and warmer water temperatures all have a negative effect on fish and other aquatic life. Fish require oxygen to breathe, photosynthesis to produce their food, and a specific water temperature range (warmer/colder depending on the species) to live in. Suspended sediment can have an even more direct impact on fish by clogging gills, reducing resistance to disease, lowering growth rates, and affecting egg and larval development by smothering eggs and benthic critters.

Beschta (1981) considered suspended sediment transport “source limited” in streams. This means that the concentration of suspended sediment in the stream depends on sediment loading from outside the stream or upstream, when referring to a specific stream segment. Walling and Webb (1987) and Salant et al. (2008) studied suspended sediment dynamics and showed that the bulk of the sediment is transported by single-flood events, usually of short duration and high magnitude, and that the relationship between the suspended sediment load and water discharge is highly variable.

Research conducted by Keppeler et al. (2003), in the Caspar Creek Experimental Watershed, suggested that suspended sediment loads increased more than 330 percent after road building. Lewis

(1998) found annual sediment load, including suspended and pond accumulations, increased 184 percent for the six-year post-harvest period (1972-1978). However, in this study the author found that the roads were located far enough away from streams that they were not a significant source. Instead, increased flow after other silvicultural practices (i.e., cutting and burning), soil disruption, and increased erosion along unbuffered streambanks were considered the primary sources of sediment.

While adding protection to the road surface with gravel can help stabilize the road sediment, finer materials are often generated from heavy road use and can wash from the roadway to a stream, further exacerbating turbidity in a stream. Bilby (1985) set up an experiment in the Johnson Creek watershed in Washington to measure the size of sediment washing from a gravel-surfaced road. After rainfall events, sediment input from the road frequently increased the levels of suspended sediment downstream of a culvert compared to upstream levels. Maximum turbidity recorded downstream was almost three times the maximum recorded upstream. The sediment was primarily very fine particles (more than 80 percent were less than 0.004 mm in size) and was attributed to erosion from the road surface rather than roadside ditches or banks.

In addition to fine sediments that stay suspended in solution, course sediments enter the waterway and settle to the bottom. These larger sediments are commonly referred to as bed load. Beschta (1981) considers bed load transport to be "flow limited" in streams, meaning that coarse-grained sediment is usually transported and re-deposited at high flow rates. Because of their larger size, bed load is not transported as readily as suspended sediment and thus doesn't cause as many water quality problems. Only during high flows, which can be generated from road construction or mass wasting, does bed load get deposited. Unlike fine-grained sediment which can cause negative impacts when it settles, course-grained sediment has the potential to act as a protective habitat for some species and their young. Bed load does become an issue when it scours the streambed and fills shallow pools with sediment. Montgomery et al. (1996) found that increases in scour depths were related to increases in stream discharge and velocity and increases in fine sediment transport. Scouring can temporarily increase suspended sediment in the water column, thereby increasing turbidity, significantly increase the mortality of buried salmonid eggs (Schenk and Bragg 2014), and reduce habitat for aquatic life. Scouring would also negatively affect eggs from other species of fish as well as benthic organisms and amphibians that dwell in the stream bed.

8 Effect of Sediment on Aquatic Life

A review of the biological effects of fine sediment in the lotic environment (Wood and Armitage 1997) summarized the effects of fine sediment suspension and deposition on benthic invertebrates. These effects include: (1) altering substrate composition, potentially affecting the suitability of the substrate for some taxa (Erman and Ligon 1988; Richards and Bacon 1994); (2) increasing drift due to sediment deposition or substrate instability (Culp et al. 1985; Rosenberg and Wiens 1978); (3) affecting respiration due to the deposition of silt on respiration structures (Lemly 1982) or low oxygen concentrations associated with silt deposits (Eriksen 1966); and (4) affecting feeding activities by impeding filter feeding due to an increase in suspended sediment concentrations (Aldridge et al. 1987) and reducing the density of prey items (Peckarsky 1984).

Water quality studies frequently use benthic macroinvertebrates at biological indicators. These organisms are relatively cheap and easy to sample and identify, and have varying sensitivity based on each species. Benthic organisms live under stones and debris on the stream bed and typically remain in their original habitat. Fish on the other hand, are inherently different from benthic organisms in that fish can move far distances if habitat conditions are not suitable for survival. Natural variability in flow, such as extreme floods and low flows associated with drought, should be expected to result in variations in the concentration of suspended solids deposited in the natural environment. Benthic faunal communities are generally expected to withstand these short-term fluxes in suspended and benthic sediments. However, continuous high levels of sediment input may completely change the natural faunal assemblages (Wood and Armitage 1997).

Fish species inhabiting a river body are either adapted to specific sediment characteristics which are not constant (e.g., seasonal and inter-annual variations) or tend to leave the area subject to excessive sediment load before returning after an event (flash flood, seasonal flood). Disturbed streams may create areas of suboptimal and possibly unusable habitat, termed 'aquatic deserts' by Sullivan and Watzin (2010). While these aquatic deserts certainly impact migratory and year-round habitat use, Sullivan and Watzin present evidence that fish species in common feeding guilds may respond differently to sediment buildup overtime making some species more susceptible to change in landscape than others.

Araujo (2011) used Monte Carlo simulations to determine that populations of both Chinook and Coho (salmon species) experienced an exponential decline with a linear increase in the number of extreme sedimentation events. In the study, Araujo (2011) determined that the more intense the road use levels, the higher the frequency and magnitude of extreme sedimentation events expected in the watershed. These extreme events then resulted in decreased numbers of spawners and harvested fish during the simulation period. Population declines were greatest for scenarios of heavy road use. The non-linear decline in both Coho and Chinook populations was likely due to the nature of the spawner-egg relationship. Further, an increased number of extreme events also led to higher variation in yearly returns. It is important to note that the results reflect the effects of suspended sediments generated by forest roads at a population level, but do not capture all the effects of forestry activities on salmonids such as changes in the input of woody debris and water temperatures.

It is important to note that not all disturbances related to forest roads cause negative impacts on salmonid population numbers (Gregory et al. 1987; Schlosser 1991; Naiman et al. 1992). Non-lethal exposure to suspended sediments may provide positive trade-offs. Moderate levels of fine sediments may benefit salmonids by contributing to increased macroinvertebrate productivity, a primary food source for salmonids (Everest et al. 1987), and naturally elevated turbidity can protect age-zero juvenile salmonids from excessive predation (Newcombe 2003). However, even though elevated suspended sediment concentrations may protect juveniles from predation, it decreases their prey-capture rates substantially

(Gregory 1991). In addition, not all populations are susceptible to suspended sediment concentrations to the same degree, depending on their population-specific adaptations. Nonetheless, the transport and deposition of fine sediments are more frequently associated with deleterious effects on the survival of aquatic organisms than with ecological benefits (Araujo 2011).

8.1 Shallow Pools

It is important to note that the presence of sediment in water bodies is normal. It is variation outside of the normal range that may pose a threat to aquatic species and there is no specific level at which all species of fish are equally affected (Sanderson 2009). To illustrate the direct impact of sediment to shallow pools, Hilliard (2009) examined off-highway vehicle road and trail systems in North Carolina and found that generally as suspended sediment increased, pool filling increased as well. Where excessive pool filling is occurring, the amount of sediment suspended in the water column during storm runoff events is more than the stream can efficiently transport, resulting in sediment deposition onto the streambed.

Shallow pools are important to maintaining critical habitats for migrating adults and rearing habitats for juveniles (Bjornn and Reiser 1991). Pools often include habitat with varying particle sizes and bed material that create a landscape of “nooks-and-crannies.” This habitat provides ideal spawning conditions, cover, and rearing habitat. Pools that lose volume from sediment support fewer fish (Bjornn et al. 1977) and fish that reside in them may suffer higher mortality (Alexander and Hansen 1986). The loss of shallow pools to increased sediment may also reduce algal production, the primary food source of higher trophic levels including many invertebrates and fish (Chutter 1969; Hynes 1970).

8.2 Temperature

As small pools fill from the effects of sediment input, the stream width to depth ratio may also change. Streams with high width to depth ratios (wide, shallow streams) experience greater temperature extremes than streams with low width to depth ratios (narrow, deep streams), with similar cross-sectional areas. Wide, shallow streams have more surface area for the exchange of radiant, evaporative and convective fluxes compared to narrow, deep streams (LeBlanc et al. 1997). These changes in temperature may result in increased adult and juvenile mortality, a decrease in aquatic amphibian and invertebrate abundance or diversity, burial of stream-bottom habitat, and decreased habitat complexity necessary to support an ecologically diverse environment (Anderson and Lockaby 2011).

Stohr and Leskie (2000) used June conditions and demonstrated the likely change in temperature estimated by the SSTEMP model over a range of width-to-depth ratios and shade conditions (Figure 3). Within a 12 percent shaded stream, the temperature can vary up to 2.23ºC based on the width to depth ratio.

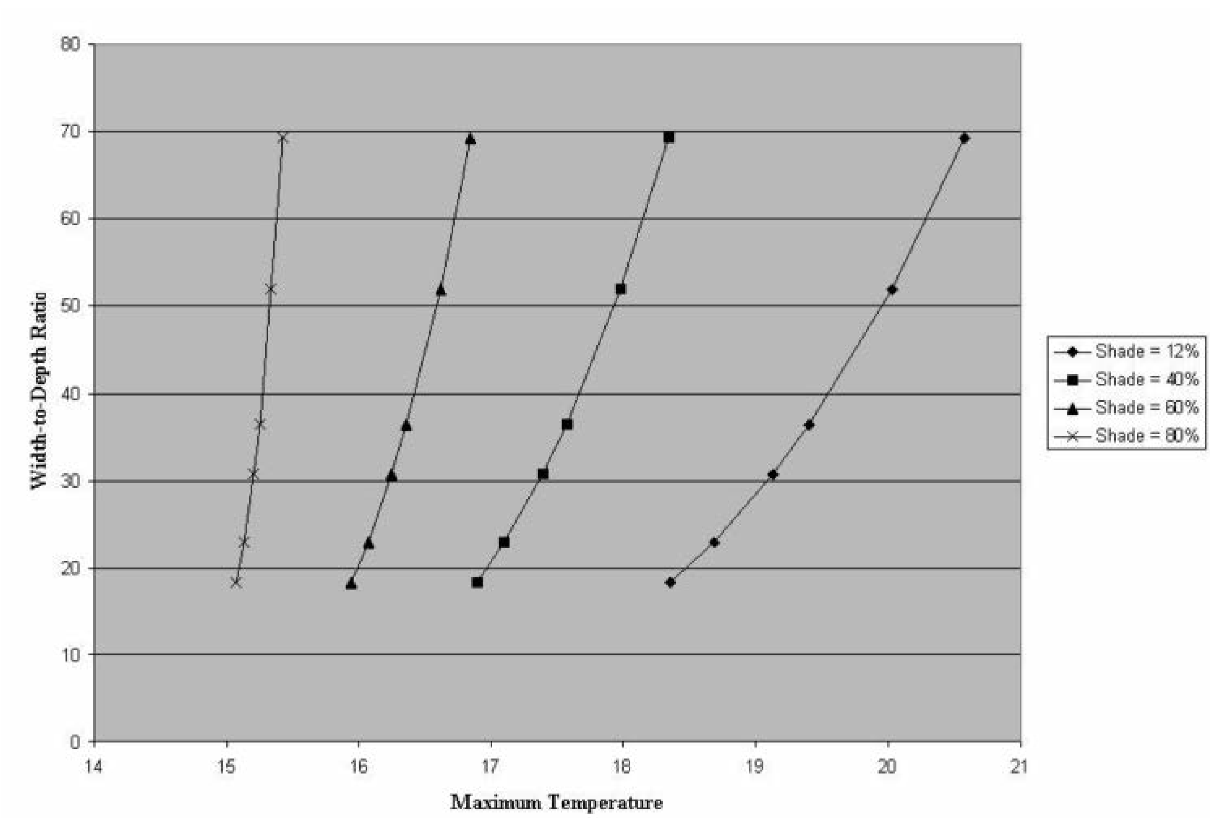

Figure 3. Change in maximum stream temperature as a function of channel width-to-depth ratio and riparian shade (Stohr and Leskie 2000)

Similar modeling conducted by LeBlanc et al. (1997) of an urbanized, groundwater-influenced stream found temperature increases of up to 1.7ºC for a stream enlarged by a factor of 1.33. The authors also noted that shade/transmissivity of riparian vegetation greatly impacts stream temperature. When forest roads remove riparian vegetation in addition to increasing the width to depth ratio through sedimentation, stream temperature is almost guaranteed to impact aquatic life in the stream.

Some aquatic species survive within a narrow temperature range and therefore are more likely to be affected when water temperature change (Magnuson et al. 1979). Several studies (Rieman and McIntyre 1993; Buchanan and Gregory 1997; Haas 2001; Selong et al. 2001) have found that in western North America, the bull trout *Salvelinus confluentus* is a highly sensitive species to changing water temperature. As a cold-water species, the bull trout is particularly vulnerable to naturally-occurring and anthropogenic changes, including riparian vegetation removal and increasing stream width to depth ratio, that increased stream temperature (Poole and Berman 2001),

9 Best Management Practices

For several decades now, BMPs have slowed, infiltrated, and treated stormwater runoff. Forest road BMPs consist of an array of practices that include but are not limited to riparian buffers, avoiding stream crossings and wet areas, building on a low to medium slope, and using water bars or similar practices to divert water from the roadway and across the forest floor. When properly applied, BMPs are effective at reducing sediment loads to streams. After assessing their BMP program, Wisconsin Department of Natural Resources (2013) found their state had an average forest road BMP compliance rate of 84 percent and BMP effectiveness of 93 percent when the BMPs were properly constructed and maintained. High BMP efficiencies were also found by NCASI (2012) from evaluating hundreds of studies, concluding that BMP implementation can cause an 80 percent reduction in sediment load to streams compared to forest road operations that do not implement BMPs.

Most forest road BMPs are easy to install or implement and are relatively cheap. One such example is the water bar, a mound of dirt across the road surface (like a “speed bump”) that intercepts and diverts water from flowing down the roadway. As previously explained, sediment is detached via erosional processes from forest roads. Concentrated runoff flows may then transport the sediment through rills and gullies along the road surface or ditches along the side of the road. BMPs, like water bars, can shorten the flow path of sediment-laden runoff by diverting and dispersing it across forest buffers. Diverting and dispersing ditch or cross drain runoff in this manner increases runoff infiltration (Elliot and Tysdal 1999) and can even prevent sediment discharge to streams (Swift and Burns 1999). Elliot et al. (2009) point out that buffers are less effective in infiltrating runoff and reducing sediment delivery to streams when soils are wet, because as soil moisture levels increase, infiltration rates decrease.

One of the most important non-structural (institutional) BMPs is good road location and design. Designing stable stream crossings, roads that adequately divert runoff to the forest floor, and isolating roads away from streams can significantly reduce and even prevent sediment from entering streams (Douglass 1974; Swift 1985; Swift and Burns 1999). Forest roads should fit the terrain, follow natural contours, not be located on steep slopes or sharp curves, and have as much distance away from sensitive areas, such as riparian zones and wetlands, as possible (USDA 2012). Roads should be located as far away from water bodies as practicable and the number of stream crossings should be minimized to reduce the likelihood of negatively impacting water quality. Recommended practices also include using the lowest amount of road needed (width, length, and number of roads) to meet the use objectives, using temporary roads whenever possible, and stabilizing the road surface with protective covering, such as shredded wood debris (USDA 2012). Another important BMP is to establish streamside management zones (SMZs). An SMZ provides a vegetated buffer along each side of a stream that maintains streambank stability, provides shade to the stream, and filters runoff before it enters the stream.

It is recommended to use existing roads whenever possible. As explained in previous sections, road construction is a significant potential source of erosion and sedimentation. Utilizing existing roads within a forested area reduces the amount of erosion, impervious road surface area, and additional tree clearing. It is recommended to perform a thorough evaluation of existing roads before using them because roads that are in poor condition may generate more sediment than a newly constructed road. When roads are no longer in use, the application of soil amendments, light tilling, and grass seed is recommended on the road surface area to prevent further erosion once the road is decommissioned.

10 Impact of Sedimentation on the Human Environment

There are many studies that document the damage sediment and other soil erosion-related pollutants cause in water bodies, however, few studies attempt to calculate the economic costs of these damages (Clark 1985). The Pennsylvania Fish and Boat Commission and Trout Unlimited stated, "sediment pollution costs residents of the Commonwealth tens of millions of dollars each year in lost revenue (e.g., hotel rooms, restaurants, etc.) associated with recreational fishing because of degraded water quality and reduced fish habitat (PA DEP 2012)." One study found that the annual cost of sediment damage in the U.S. ranged from $1 billion to $13 billion (Clark 1985, 1985 dollars) while another found it cost approximately $16 billion (Osterkamp et al. 1988, 1988 dollars). Clark (1985) also indicated that erosion-related pollutants such as suspended sediments can change the recreational value of impacted areas. For example, increased suspended sediments may reduce the value of freshwater fishing by reducing fish populations or shifting taxa away from "high value" game fish that draw in anglers. Siltation and weed growth may physically interfere with boating and swimming making these activities less desirable, and thus less of a recreation or tourist destination in affected watersheds (Clark 1985). Hunting is also affected because aquatic vegetation and wildlife affected by sedimentation and pollutant are food sources for many waterfowl. Other forms of recreation indirectly affected by sedimentation include hiking, swimming, and sightseeing (PA DEP 2012).

Forest roads provide access for a multitude of recreational activities, including recreational driving (sightseeing), camping, fishing, hunting, and foraging (mushrooms, berries, etc.). For example, over 200 million recreational activity days per year were made by people to federal lands in the Interior Columbia Basin Ecosystem Management Project assessment area, 45 percent of which were for sightseeing from automobiles (Quigley and Arbelbide 1997). Forest roads also provide access points of departure for trail uses such as hiking, horseback riding, and off-roading. In fact, points of departure for wilderness access are often found on low volume forest roads (NCASI 2003). The public's use of forest roads in this manner can cause erosion, especially horseback riding and off-roading, although the impact is typically less than from silvicultural activity. Forest roads may also provide increased access to sensitive ecosystems where recreational activities increase the potential for wildfire and other environmental harm (Weston 2010).

Forests in the 20 states and Washington, DC, served by the USFS northeastern area of state and private forests help protect more than 1,600 drinking water supplies that are the source of water for more than 52 million Americans (USDA 2005). More than two-thirds of the population in this region depend on drinking water from streams, lakes, and reservoirs. The quality of this water depends, in part, on the forest lands in their watersheds. Lewis (1998) concluded that sediment reduces the capacity of drinking water reservoirs and can make the water undrinkable, unless it is further treated. The author also found that sediment in irrigation water may shorten the life of pumps and will reduce infiltration capacity once the irrigation water is applied to soil.

11 Conclusion

Studies have consistently found forest roads as a major potential source of sediment in the forested environment. Sediment is generated from forest road surfaces, ditches, cut slopes, and fill slopes through such processes as overland flow, rill and gully erosion, and landslides. Sediment production is greatest during and immediately after road construction, however sediment production can occur throughout the lifespan of a road, even after it is no longer in use. Forest roads can also convey sediment by increasing the flow path of stormwater runoff. If sediment-laden stormwater is delivered to a water body, it can have deleterious effects on both water quality and aquatic health. When properly applied, forest road BMPs can significantly reduce sediment production and transport. Appropriate road design, location, construction, and maintenance can help ensure forest roads achieve their intended use without negatively impacting water quality. This literature review supports EPA’s decision to not regulate forest road discharges under an NPDES stormwater permit. Existing BMP programs have proven successful in reducing the effects of sedimentation from forest roads.

12 Additional Research

Despite the years of research that has gone into evaluating the effects of sedimentation from forest roads and the associated processes that cause it, data gaps remain. Anderson and Lockaby (2011) categorized data gaps they found in the literature into four groups: effects of harvesting on water quality and quantity, scale of sediment delivery, water and sediment yields from forest roads, and BMP effectiveness. There is a need for increased use of sediment tracers, including nuclide and isotropic tracers (Wallbrink and Coke 2002) to identify the source of sediment and to track its delivery to streams (Miller et al. 1985; Bilby et al. 1989; Walling 2005). Fu et al. (2010) suggested incorporating sediment tracer experiments into modeling efforts and improving the modeling of road surface erosion and sediment delivery processes, improve understanding buildup-wash off processes, and expand our knowledge of watershed-scale hydrologic effects caused by roads, especially how it affects subsurface flow interception.

Additional research should evaluate how short-term disturbances caused by sediment affect water quality and aquatic health over the long-term (Anderson and Lockaby 2011). Long-term stream monitoring that measure biological, chemical, and physical characteristics of the stream may improve our understanding of how a water body copes with additional sediment loads deposited during rain events. Researchers should compare roads built over 30 years ago to those built more recently to determine how improved road system designs have impacted soil losses from the road surface and landslides (Gucinski et al. 2001). Such research can help improve future road design and provide support for legacy road restoration efforts when an older road is identified as a major sediment source. We should also further evaluate sediment yields from roads that were abandoned after use (not properly decommissioned) compared to roads that were properly decommissioned or restored for another use (Anderson and Lockaby 2011). Finally, continuous research into BMP design, application, maintenance, costs, and efficiency is needed to support our understanding of the benefits of BMPs and to develop new and innovative techniques to further reduce sediment loads delivered to streams.

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