Sediment Production and Delivery from Unpaved Roads: A Little-recognized but Significant Sediment Source

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Abstract

Unpaved roads can be a major sediment source, especially in forested areas where the high infiltration rates and nearly continuous ground cover result in very low levels of overland flow and erosion. Yet there is relatively little recognition of the extent to which unpaved roads can adversely affect hillslope erosion, local water quality, aquatic habitat, and increase watershed-scale sediment yields. The objectives of this paper are to: 1) summarize the key processes that control road sediment runoff and erosion; 2) summarize the key processes that affect the delivery of road surface runoff and erosion to streams or other water bodies; 3) show how wildfires can dramatically increase road surface erosion and sediment delivery; and 4) use this understanding to show how road surface erosion and sediment delivery can be minimized.

Road Surface Runoff and Sediment Production

Unpaved roads typically have infiltration rates of only 1-5 mm h^{-1}, resulting in overland flow from nearly all rainstorms as well as snowmelt. In many cases the road surface is almost completely bare, and has large amounts of loose fine sediment generated by vehicle traffic or grading (Figure 1). The combination of surface runoff and readily-available sediment results in annual sediment production rates that typically are around 1 kg per square meter of active road surface per year (4.5 tons ac^{-1} yr^{-1}), with values of around 7 kg m^{-2} (30 tons ac^{-1} yr^{-1}) in highly erodible terrain with summer thunderstorms in the western US (Welsh, 2007) and up to 20 kg m^{-2} (90 tons ac^{-1} yr^{-1}) in sub-tropical high rainfall areas such as Puerto Rico (Ramos-Scharrón and Figueroa-Sánchez, 2017).

The key controls on runoff and sediment production are relatively well known (Fu et al., 2009), but sediment production from unpaved roads is not easily predicted because so many factors are involved. Model predictions are usually based on road segments, where a segment is a hydrologically distinct unit (e.g., the portion of a road between successive waterbars). Two of the most important road segment characteristics for predicting road surface runoff and erosion are road segment area and slope. Road segment area governs the amount of runoff (Q) as indicated by equation 1:

$$Q = (P-I)\,A \qquad \text{(eq. 1)}$$

where P is precipitation and I is infiltration, both in length per unit time, and A is the active road surface area. Road segment slope, in combination with the depth of runoff, governs the amount of energy for detaching and transporting soil particles. Road sediment production and rilling are typically much more sensitive to segment slope than segment area (Figure 2) (Fu *et al.*, 2009).

Figure 1. Unpaved road with drainage rill and a sediment fence to measure sediment production from a road segment on the Pike-San Isabel National Forest in central Colorado, USA.

In addition to road surface area, slope, and rainfall intensity, the supply of readily erodible fine sediment is another major control on road sediment production. The amount of fine sediment is a complex function of the amount and type of traffic, lithology and soil texture, time since grading or road construction, surface cover (including rocks), and antecedent precipitation. A fifth key factor is road design, as this controls whether the road surface runoff is directed into an inside ditch ("insloped"), flows down the road surface (planar or rutted), drains off the downslope side of the road in a dispersed manner ("outsloped"), or flows from the middle off to each side ("crowned") (Weaver *et al.*, 2014). Planar and rutted roads generally have the highest sediment production rates (Fig. 2). Several empirical and physically-based models have been developed to predict road runoff and sediment production at the segment scale, including the semi- empirical SEDMODL2 (NCASI) and READI (Benda et al., 2019), the more physically-

Figure 2. Rills formed on an unpaved road segment in the Sierra Nevada of California due in large part to the steeper slope of the segment and the lack of proper drainage design. This road segment would require relatively frequent grading to remain drivable by normal vehicles at reasonable speeds.

based WEPP:Road (Elliot , 2004), and GRAIP/GRAIP-Lite (Black *et al*. 2012; Cissel *et al*., 2012). From a practical perspective the amount of road surface erosion and rilling are important also because these determine how often a road needs to be graded, which can be a substantial cost to land managers (Figure 2).

Road Sediment Delivery

For natural resource managers, the most critical question is whether the runoff and sediment from unpaved roads is degrading water quality, increasing peak flows and sediment yields, and/or adversely affecting fish habitat or other aquatic resources. These effects can be expressed both locally, such as in a stream immediately below a road crossing or adjacent to a heavily trafficked unpaved road, and cumulatively at the watershed scale, such as reservoir sedimentation or in a bay or other water body. Any effort to assess these effects requires both an estimation of road surface erosion and how much of the road surface runoff and sediment is being delivered to a stream or other water body ("road-stream connectivity"). Field studies have shown that the percent of road segments or percent of road length connected to streams can range from around 10% to 35% (MacDonald and Coe, 2008). As with road surface erosion, we understand the key factors controlling the delivery of road surface runoff and sediment for a given storm, but accurate predictions are still problematic.

The length of the flow path between a road drain and a stream or water body is generally the most important variable for predicting whether a road segment is connected. Key controls on the length of rills and sediment plumes are the amount of road surface runoff, which depends on rainfall intensity and duration along with road segment area, and the slope, roughness, and infiltration rate along the flow path. Especially in forested areas, the rills and sediment plumes from roads rarely extend for more than 30-50 m (Benda et al., 2019). At the watershed scale road-stream connectivity is heavily influenced by the number of road-stream crossings, which depends on the density and layout of the road network along with the stream channel density. Each of the models mentioned above also attempts to assess road-stream connectivity, although only WEPP:Road and to a lesser extent READI use process-based calculations rather than empirical delivery curves.

Land use activities can greatly increase the amount and delivery of sediment from unpaved roads. Ground-based logging often results in a network of skid trails to access and then yard the trees to landings, and the resulting skid trails effectively behave like unpaved roads and can reach very high densities (Sidle et al., 2004). In areas burned at high and moderate severity, unpaved roads are a major concern because wildfires greatly increase road-stream connectivity as well as road surface erosion (Figure 3) (Sosa-Pérez and MacDonald, 2016). These increases are due to the low post-fire infiltration rates of less than 10 mm hr^{-1} and the loss of surface roughness to slow the runoff and trap sediment. The much larger amounts of post-fire surface runoff and sediment draining onto roads from upslope can greatly increase road surface erosion and the amount of water and sediment that is discharged from road segments onto hillslopes. The result is that road-stream connectivity may approach 100% after high and moderate severity wildfires, regardless of the distance between a road and a stream (Figure 3) (Sosa-Pérez and MacDonald, 2016). Trails for off-highway vehicles often have even higher surface erosion rates than unpaved roads due to the aggressive driving techniques and knobby tires that generate more loose sediment than regular traffic ((Welsh, 2007; Sosa-Pérez and MacDonald, 2017.)

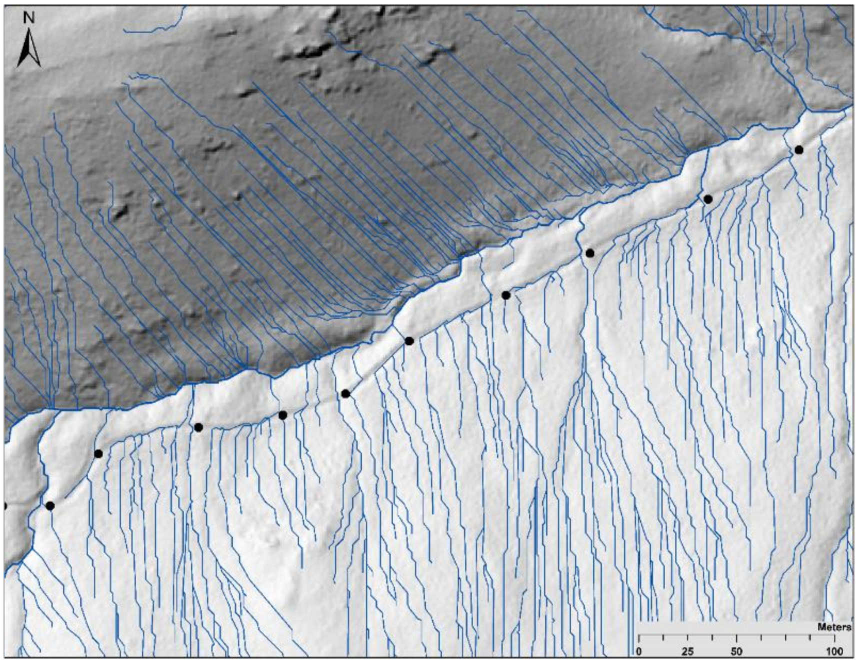

Figure 3. Predicted overland flow lines in a burned area with an unpaved road on the south side of the creek that runs from lower left to upper right, and the opposite hillslope with no road (shown as a darker, shaded hillslope). The flow lines show how the upslope flow lines are intercepted by the road, and the runoff is accumulated and then discharged as concentrated flow, with typically only one drain per segment (black dots show the beginning and end of each road segment as identified by a field survey). In every case the road runoff reaches the stream.

Reducing Road Surface Erosion and Road-stream Connectivity

The techniques for reducing road surface erosion and road-stream connectivity are relatively well understood (Weaver et al., 2014). One of the easiest and most effective techniques is to reduce the spacing between road drains. This first reduces road surface erosion by reducing the volume and velocity of road surface runoff, but a possibly more important effect is that the smaller volumes of runoff and sediment are more likely to infiltrate or be trapped before reaching a stream. Outsloping the road can dramatically reduce road sediment production and delivery as long as the road surface does not become rutted by the passage of vehicles; outsloping is especially difficult to maintain if a road is subject to traffic in wet weather. Rocking the road surface can reduce road sediment production rates by a factor of around 4 to 10 (e.g., Swift, 1984; Coe, 2006), depending on the depth and quality of the rock as well as the type and amount of traffic. However, rocking is usually much more expensive than installing additional drainage dips or waterbars. Land managers are increasingly trying to reduce road sediment impacts by closing or decommissioning roads adjacent to streams, but this can be relatively expensive, especially if replacement roads have to be constructed further upslope or on ridgetops.

Conclusions

Unpaved roads can be a major sediment source with severe downstream impacts. In one study area in Colorado, unpaved roads are probably contributing a similar amount of sediment over time to the stream network as the pulsed sediment input from high severity fires (MacDonald and Larsen, 2009). In the U.S. Virgin Islands, unpaved roads can be the predominant sediment source that threatens the surrounding coral reefs. Although sediment-related impacts from unpaved roads have been the focus of recent regulations and/or BMP guidance in some western states (e.g., California, Oregon, Washington), a much greater awareness is needed by the public, regulators, and resource managers if we are to develop the political will and resources needed to address the persistent and widespread runoff, erosion, and sediment problems posed by unpaved roads.

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