Road Sediment Production and Delivery: Processes and Management

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Abstract. Unpaved roads are often considered to be the predominant sediment source in forested catchments. In steep, wet climates roads can cause a 10- to 300-fold increase in the landslide erosion rate, and this increase is due to the effects of roads on hillslope flow paths and the structural integrity of hillslopes. The proportion of sediment that is delivered to the stream will generally be very high for road-induced failures in hollows and inner gorge landforms, and much lower for planar hillslope failures. The pulsed input of sediment from road-induced landsliding can greatly alter stream channel habitat and morphology.

Unpaved roads can increase sediment production rates by more than an order of magnitude as a result of road surface erosion. The high surface erosion rate stems from the generation of surface runoff from the highly compacted road travelway, the lack of surface cover, and the availability of fine sediment due to traffic and road maintenance procedures such as grading. Sediment delivery to streams occurs primarily at road-stream crossings and secondarily by road-induced gullies. The proportion of the road network that is connected to the stream network is primarily a function of mean annual precipitation (R^2=0.9), and is increased by about 40% in the absence of any engineered drainage structures. The chronic input of the fine sediment from roads can have adverse effects on freshwater aquatic ecosystems as well as coral reefs.

Our present understanding of road surface erosion processes is good, but our models to predict road surface erosion and landsliding are much better for relative than absolute predictions. Climate change can greatly increase road-induced landslides and road surface erosion by increasing the magnitude of large storm events and increasing the amount of rain relative to snow. Extensive field surveys also show that relatively few road segments typically generate most of the road-related increases in sediment yields. Road surface erosion, the risk of road-induced landslides, and road sediment delivery can be greatly decreased by improved road designs and maintenance practices. Hence the greatest needs are to develop and provide land managers with the tools for identifying high-risk segments, and then to make the necessary investments in road reconstruction and restoration.

1. Introduction

Sediment production and delivery in steep, forested catchments is typically dominated by low frequency, high magnitude erosion events such as landslides or debris flows. These occur against a background of relatively low sediment production and delivery rates (Reeves et al., 1995; Kirchner et al., 2001). In unmanaged catchments the pulses of surface erosion and mass wasting are driven by storms, fires, and earthquakes (Benda and Dunne, 1997; Miller et al., 2003). Aquatic species are adapted to these periodic disturbances, and periodic erosional events may be necessary to sustain long-term ecosystem diversity and productivity (Reeves et al., 1995).

Unpaved roads are one of the most common types of man-induced disturbances. Roads induce surface runoff and can alter subsurface flow on hillslopes, and this can affect the magnitude and timing of surface runoff (Jones et al., 2000; Wemple et al., 2001; Wemple et al., 2004). By exposing the soil surface and increasing and concentrating runoff, surface erosion can be greatly increased on each of the different parts of the road prism (i.e., cutslope, travelway, and fillslope) (Figure 1). The surface runoff from roads also can initiate gully erosion below the road prism. Roads also can increase landsliding on road cutslopes, fillslopes, and hillslopes by altering flowpaths as well as altering the strength, loading, and pore water pressures on hillslopes (Reid and Dunne, 1984; Megahan et al., 1991; Megahan et al., 2001; Wemple et al., 2001).

The magnitude and relative dominance of these different road erosion processes is driven by variations in climate, geology, physiography, road design, road construction, and road maintenance practices (Jones et al. 2000, Wemple et al. 2001). As such, there can be considerable variation in the type, magnitude, and frequency of road-related sediment production within and between regions. Hence the objectives of this paper are to: 1) describe the underlying processes of road sediment production from surface erosion and landsliding; 2) compare road sediment production rates from surface erosion and landslides in different environments; 3) compare the delivery and potential off-site effects of road-related sediment from surface erosion and mass movements, respectively; and 4) indicate the extent to which best management practices (BMPs) can minimize road sediment production and delivery.

2. Sediment Production from Forest Roads

2.1. Surface Erosion from Forest Roads

The high infiltration rates and dense vegetative cover on most undisturbed forested hilllslopes means that surface runoff is relatively rare and hillslope erosion rates are very low. In contrast, unpaved roads can increase surface erosion rates by two or more orders of magnitude relative to undisturbed hillslopes (MacDonald and Coe, 2007). Over the past two decades research in a variety of environments has led to a relatively good understanding of road runoff and erosion processes.

The first key point is that road travelways are highly compacted and have very low infiltration rates (typically less than 5.0 mm hr^{-1}) (Reid and Dunne, 1984; Luce and Cundy, 1994; Loague and Kyriakidis, 1997; Luce, 1997; Ziegler and Giambelluca, 1997). This results in the generation of infiltration-excess (Horton) overland flow even during small rainfall events (Ziegler and Giambelluca, 1997). In addition, road cutslopes can intercept transient hillslope groundwater (i.e., subsurface stormflow) when the height of the cutslope exceeds the depth to the water table (Ziegler et al., 2001b) (Figure 2). The interception of subsurface stormflow (SSF) is threshold dominated, as SSF only occurs when precipitation exceeds 25-50 mm under wet antecedent conditions (Weiler et al., 2005). In some cases the interception of SSF can account for more than 90% of the road surface runoff (LaMarche and Lettenmaier, 2001; Wemple and Jones, 2003).

The amount and energy of surface runoff determines the erosive force applied to the road prism by overland flow (Luce and Black, 1999). The road prism can be broken into different process domains for surface erosion based on the interaction of flowpath length (L), which largely controls the amount of runoff, and slope (S), which is the primary control on the energy of the runoff. On road cutslopes and road fillslopes the slope can be very steep (Figure 1), but the limited slope length limits the amount of flow accumulation and hence the potential for hydraulic erosion. As a result, road cutslope and fillslope erosion is primarily through rainsplash (if there is not much cover), sheetwash, and rill erosion if the slope length allows sufficient runoff accumulation. The limited data suggests that cutslope erosion is usually much less than the erosion from the road travelway (Ramos-Scharrón and MacDonald, 2007).

Figure 1. A picture of a reconstructed outsloped native surface road on a highly erodible, weathered granodioritic hillslope in northern California, USA. The road prism is comprised of the cutslope, travelway, and fillslope, and the arrows show the potential length of overland flow for each of these pathways. Note how the rill networks on the travelway concentrate the road surface runoff before it is discharged onto the fillslope. The extensive rilling is due to poor compaction during road reconstruction.

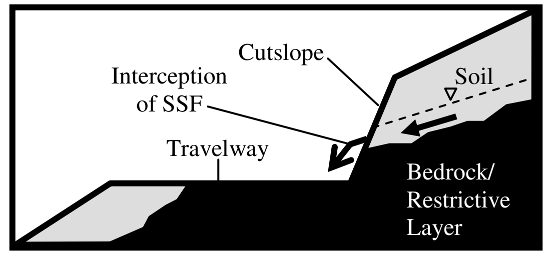

Figure 2. Schematic showing how subsurface stormflow (SSF) along the soil-bedrock interface can be intercepted by a road cutslope to create overland flow (modified from Ziegler et al., 2001b). from clearcut hillslopes (Sidle and Ochiai, 2006).

The slope of the travelway is usually limited to about 10-12% in order to facilitate traffic and maximize safety, but runoff can accumulate along the travelway unless it is strongly outsloped or insloped (Figure 1). Detailed road surveys indicate that the average road segment length is about 50-70 m for forested areas in the western U.S. In many cases road runoff is prevented from running off the travelway by wheel ruts, and this can result in extensive rill or gully erosion on the road surface. Inboard ditches also collect and concentrate runoff with a resulting risk of ditch incision and widening. Road fillslopes below road drainage outlets (i.e., relief culverts, rolling dips, and waterbars) are subject to the greatest erosive forces because they are steep and the potentially large volume of runoff draining to that point (Figure 2). The large volumes of water from longer road segments also can induce gully erosion below drainage outlets (Montgomery, 1994; Wemple et al., 1996). Gully erosion can be particularly severe when roads divert stream channels at road-stream crossings, and route the streamflow down the road or onto hillslopes.

The erodibility of the road prism varies as result of time since construction, maintenance activites (i.e., grading), soil texture, ground cover, and traffic (Luce and Black, 2001a; Ramos-Scharrón and MacDonald, 2005; Ziegler et al., 2001a). Rainsplash erosion on roads is common due to the relative lack of vegetative cover, and can account for up to 38-48% of total sediment production on freshly disturbed road travelways (Ziegler et al., 2000). Rainsplash erosion is highest on the road travelway, since this portion of the road prism is most frequently disturbed by traffic and typically has less vegetative cover than the adjacent cutslopes and fillslopes (Figure 1).

Sediment production rates for cutslopes, travelways, and fillslopes are highest immediately after road construction, with erosion rates declining rapidly within 1-2 years (Megahan, 1974). Fine-textured soils are the most susceptible to surface erosion, with siltier soils producing 4-9 times more sediment than soils dominated by sand or gravel (Luce and Black, 1999; Sugden and Woods, 2007). Soils with higher rock content are more resistant to erosion and these soils typically have lower erosion rates (Sugden and Woods, 2007).

Table 1. Surface erosion rates for the travelway, cutslope, and fillslope for different study locations in megagrams (10^6 grams) per hectare of road per year. Assuming an average road density of 4 km km^{-2} and an average road width of 6 m, these rates would apply to 2.4% of the catchment area. On this basis, multiplying these sediment production rates by 0.024 allows a direct comparison with the sediment production rates from road-induced landslides in Table 2. Data compiled by Carlos Ramos-Scharrón.

Study location	Portion of road prism	Sediment production rate (Mg ha^{-1} yr^{-1})	Reference
North Carolina, USA	Travelway	1143	Lieberman & Hoover, 1948
North Carolina, USA	Travelway	7110	Hoover, 1952
Idaho Batholith, USA	Travelway	73	Megahan & Kidd, 1972
Idaho Batholith, USA	Travelway	20	Megahan, 1975
Washington, USA	Travelway	4.8 – 66	Wald, 1975
Southeast, USA	Travelway	8 -120	Dissmeyer, 1976
North Carolina, USA	Travelway	37	Simons et al., 1978
Northeast Oregon, USA	Travelway	0 – 7	Buckhouse & Gaither, 1982
Northwest Washington, USA	Travelway	1 – 1010	Reid & Dunne, 1984
North Carolina, USA	Travelway	0.3 - 52.4	Swift, 1984
Western Washington, USA	Travelway	52	Bilby, 1985
Idaho Batholith, USA	Travelway	23 - 76	Vincent, 1985
New Zealand	Travelway	0 – 113	Fransen et al., 2001
Poland	Travelway	98	Froehlich, 1991
Australia	Travelway	50 – 90	Grayson et al., 1993
Oregon Coast Range, USA	Travelway	1.8 – 37	Luce and Black, 1999
U.S. Virgin Islands	Travelway	0.46 – 74	MacDonald et al., 2001
U.S. Virgin Islands	Travelway	74	Ramos-Scharrón & MacDonald, 2005
Sierra Nevada CA, USA	Travelway	0.002 - 40	Coe, 2006
North Coast CA, USA	Travelway	0.5 – 46	Barrett & Tomberlin, 2008
Georgia, USA	Cutslopes	26 – 108	Diseker & Richardson, 1962
Oregon, USA	Cutslopes	153 – 370	Wilson, 1963
Oregon, USA	Cutslopes	75 - 105	Dyrness, 1970; 1975
Idaho Batholith, USA	Cutslopes	150 - 165	Megahan, 1980
New Guinea	Cutslopes	1050	Blong & Humphreys, 1982
New South Wales, Australia	Cutslopes	36 - 58	Riley, 1988
South Island, New Zealand	Cutslopes	52 - 152	Fahey & Coker, 1989; 1992
Idaho Batholith, USA	Cutslopes	0.1 - 248	Megahan et al., 2001
Idaho Batholith, USA	Fillslopes	107	Bethlahmy & Kidd, 1966
Idaho Batholith, USA	Fillslopes	12	Megahan, 1978
South Island, New Zealand	Fillslopes	1 - 12.0	Fahey & Coker, 1989; 1992

Vegetative cover can protect the soil against surface erosion, and erosion from cutslopes and fillslopes decline over time as they revegetate. Road travelways and inboard ditches are subjected to maintenance activities such as grading, and this removes the surface cover and can greatly increase the supply of easily-erodible sediment. Recent studies have shown that grading can increase erosion rates from 70% to more than an order of magnitude relative to ungraded roads (Luce and Black, 2001b; Ramos-Scharrón and MacDonald, 2005). Surface erosion rates decline exponentially to a baseline erosion rate following initial construction or grading, and this rapid decline is due to the rapid depletion of the readily erodible material and the subsequent armoring of the road prism (Megahan, 1974). (Megahan, 1974; Ziegler et al., 2001). Higher traffic levels increase the supply of fine material, and this is a major reason why traffic can increase sediment production rates by 2-1000 times (Reid and Dunne, 1984; Ramos-Scharrón and MacDonald, 2005). Dry ravel from steep cutslopes can provide sediment to an inside ditch and the road travelway and thereby sustain higher surface erosion rates.

The variations in rainfall, soil texture, traffic, and other controlling factors mean that road surface erosion rates vary over several orders of magnitude (Table 1). Both empirical and physically-based road surface erosion models have been developed, and these typically include key variables such as precipitation or rainfall erosivity, road slope, road area or length, road surface slope, soil texture, time since grading, and traffic. Unfortunately it is still very difficult to accurate predict road surface erosion for several reasons. First, many of these variables interact (e.g., traffic simulataneously affects infiltration rates, road surface cover, and the amount of erodible material on the road surface). Second, the road surface characteristics and drainage patterns can be verydynamic as wheel ruts develop or waterbars break down. Third, most road erosion models only account for erosion due to infiltration-excess overland flow, even though the interception of SSF can be an important source of road surface runoff (e.g., Wemple and Jones, 2003). Fourth, detailed road survey data need to be collected to predict surface erosion rates for each road segment. Finally, the paucity of validation studies for road surface erosion models means that the models are most useful for predicting relative rather than absolute road surface erosion rates.

2.2. Landslide Erosion from Forest Roads

Forest roads increase landsliding by disrupting the balance of driving and resisting forces acting upon and within hillslopes. As shown in Figure 3, road-related increases in landsliding are commonly attributed to: 1) oversteepening and/or overloading of downslope areas by road fills; 2) removing support for unstable hillslopes by undercutting road cutslopes; and 3) and concentrating road surface runoff onto potentially unstable portions of the road fillslope and lower hillslopes (Benda et al., 1998; Sidle and Ochiai, 2006).

Landsliding from roads can exceed natural landsliding rates by one to two orders of magnitude (Table 2). Sediment production rates from road-induced landslides are also an order of magnitude higher than from clearcut hillslopes (Sidle and Ochiai, 2006).

Road-induced landsliding is generally only an issue in relatively steep terrain, with most road-initiated failures occurring on hillslopes greater than 31-39° (i.e., 60-80%) (Chatwin, 1994; Montgomery, 1994; Benda et al., 1998; Veldhuisen and Russell, 1999). Landslides initiated from fillslopes are typically larger

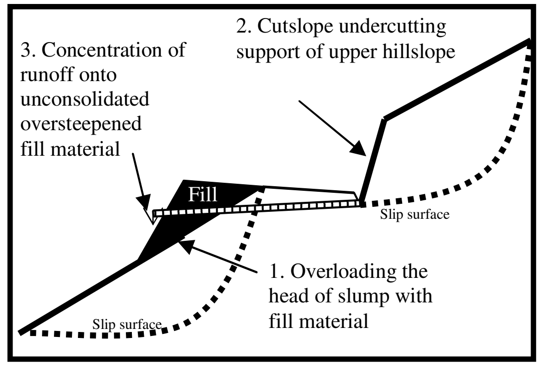

Figure 3. Schematic showing how a road increases the likelihood of landsliding (modified from Benda et al., 1998).

than those initiated from cutslopes (Wemple et a., 2001). Fill material is particularly unstable when it is placed on slopes greater than 35° and on unstable landforms such as colluvial hollows and inner gorges (Chatwin, 1994; Benda et al., 1998). Fillslope failures are more likely on cut-and-fill roads and can be largely eliminated by the more costly approach of full bench construction (Figure 4). This design excavates a bench into the hillslope that is equal to the entire width of the travelway (Figure 4), but the trade-off is that this generates a much higher cutslope.

Cutslope failures are a common occurrence in steep areas as a result of the oversteepened hillslopes (Figure 3). By reducing the support at the toe of unstable features (i.e., undercutting), cutslopes can increase the likelihood of rotational sliding. The potential for oversteepening, undercutting unstable features, and intercepting subsurface stormflow is greatest on fully benched roads because of the increased cutslope height (Figure 4). Cutslopes also

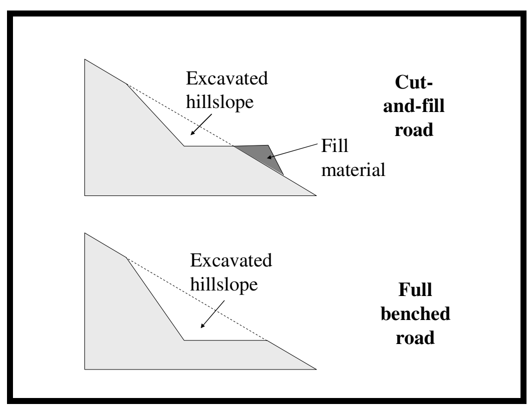

Figure 4. Schematic showing how different road designs affect slope stability. (a) A cut-and-fill road attempts to balance the amount of excavation with the amount of fill necessary to create the desired road width. (b) A full benched road requires more extensive excavation and a higher cutslope, but the excavated material is removed rather than being placed on the hillslope.

Table 2. Sediment production rates from road-induced landslides in different forested areas (modified from Sidle and Ochiai, 2006).

Study Location	Sediment production rate (Mg ha^{-1} yr^{-1})	Increase over natural rate (times)	Reference
Coastal SW British Columbia, Canada	3.8	27	O'Loughlin, 1972
Western Oregon Cascades, USA	34	30	Swanson and Dryness, 1975
Western Oregon Cascades, USA	202	337	Morrison, 1975
Oregon Coast Range, USA	21	50	Swanson et al., 1977
South Island, New Zealand	28		Mosely, 1980
Western Oregon Cascades, USA	21.2	44	Marion, 1981
Oregon Klamath Mountains, USA	36	64	Amaranthus et al., 1985
North Coast California, USA	64		Weaver et al., 1995
North Coast California, USA	15		Rice, 1999

expose the hillslope to weathering, which can progressively decrease the strength of the hillslope materials. A downslope or fillslope failure also can be initiated if a cutslope slide plugs the inside ditch and the road runoff is then directed onto a fillslope or hillslope (Wemple et al., 2001).

In many cases the increase in landsliding due to roads is a result of the hydrological changes rather than just the overloading, steepening, or undercutting of hillslopes (Sidle and Ochiai, 2006). Roads increase the amount of surface runoff and concentrate this flow. When this water is routed onto fillslopes or hillslopes this can greatly decrease their stability as a result of both the additional weight and the increase in pore water pressures. The decrease in permeability between the cutslope and the compacted road surface also can decrease the stability of the cutslope by increasing pore water pressures at the base of the cutslope (Dutton et al., 2005).

In the Pacific Northwest (USA), landslides can occur on steep slopes (i.e., >31˚) when road lengths of 60-130 m discharge overland flow below the outlets of drainage structures (Montgomery, 1994). Roads crossing steep midslopes have a high likelihood of intercepting subsurface stormflow, and cutslope and fillslope landslides are particularly common along midslope roads (Figure 5) (Wemple et al., 2001; Sidle and Ochiai, 2006). Midslopes are also common locations for unstable landforms such as colluvial hollows (Dietrich et al., 1993), and road drainage routed into colluvial hollows increases their likelihood of failure. Culverts at road-channel crossings can plug or overtop during storms, leading to catastrophic failure of the road fill and the initiation of debris flows (Furniss et al., 1998).

The prediction of road-related landsliding is difficult given the stochastic nature of landslide initiation, variability in road design and construction, and the inability to represent many of the causal processes for road-landslide interactions. Slope stability models such as SHALSTAB and SINMAP are useful for predicting the relative risk of failure and as landscape stratification tools. For management purposes these spatially-explicit estimates must be followed by field-based slope stability assessments to better identify the risk for a specific area and determine the best way to minimize the risk of road-related landslides.

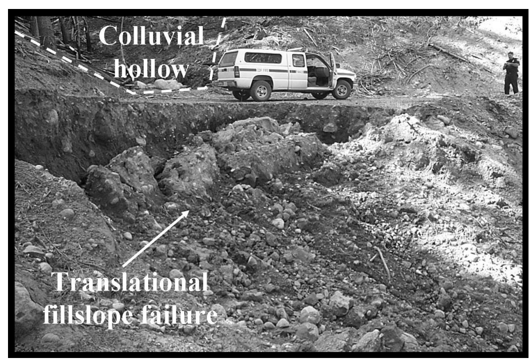

Figure 5. A translational fillslope failure directly below a colluvial hollow. Colluvial hollows concentrate SSF, so placing fill material in these landforms can increase the likelihood of landsliding.

3. Sediment Delivery from Forest Roads

3.1. Sediment Delivery from Road Surface Erosion

The delivery of road-related surface erosion is of particular concern because it is generally fine-grained (sand sized or smaller) (Ramos-Scharron and MacDonald, 2005), and this material is particularly detrimental to many organisms (Waters 1995). Connectivity refers to the proportion of roads that drain directly to streams or other water bodies.

Surveys indicate that the proportion of connected roads is strongly controlled by road location, road design, and the factors that control the amount of road runoff. In the western U.S. road-stream crossings account for 30-75% of the connected road length (Wemple et al., 1996; Bowling and Lettenmaier, 2001; La Marche and Lettenmaier, 2001; Coe, 2006). It follows that road sediment delivery is highly dependent on stream density, as this affects both the number of road-stream crossings and the proximity of the roads to the stream channel network.

The delivery of road runoff and sediment to streams generally decreases as the distance between a road and a stream increases. The high infiltration rates and high surface roughness of most forested hillslopes means that buffer strips can be quite effective at trapping road-related sediment. If the road runoff is dispersed, the sediment from road surface erosion rarely travels more than 30 m on vegetated hillslopes (Megahan and Ketcheson, 1996; Brake et al., 1999; Coe, 2006). However, if the road runoff is concentrated into a single drainage outlet, the runoff and sediment can induce gullying and travel 3-4 times further than when it is dispersed (Megahan and Ketcheson, 1996; Coe, 2006).

The development of gullies as a result of concentrated runoff is the second most important mechanism for road-stream connectivity, as 9-35% of the total road length can be connected to the channel network via this process (Wemple et al., 1996; Croke and Mockler, 2001; Coe, 2006). Since longer road segments result in more runoff and more erosive power below road drainage outlets, roads with inadequate drainage are much more likely to induce gullies and be connected to the stream channel network that roads with dispersed or more frequent drainage. Modeling studies have suggested that road-stream connectivity will increase with the amount of intercepted subsurface flow (Bowling and Lettenmaier, 2001; La Marche and Lettenmaier, 2001), but there are not yet enough field studies to verify this relationship.

A meta-analysis of the available data indicates that road-stream connectivity is a relatively simple function of annual precipitation and the presence of engineered drainage structures (Coe, 2006). The empirical predictive equation developed from 11 studies in different parts of the world is:

$$C = 12.9 + 0.016P + 39.5M \qquad (1)$$

where C is the percent of road length or road segments that are connected to the channel network, P is the mean annual precipitation in millimeters, and M is a binary variable with 0 representing roads with drainage structures, and 1 representing roads without drainage structures (R^2=0.92; p<0.0001). This predictive equation indicates the importance of precipitation in controlling both the amount of runoff and the density of the stream network. The binary variable indicates that well-designed roads with regular drainage will decrease road connectedness and hence road sediment delivery by at least 40%.

The connectivity between roads and streams is important because any increase in fine sediment loads will adversely affect water quality, macroinvertebrate populations, fish habitat, salmonid populations, and the health of coral reefs (Everest et al., 1987; Waters, 1995; Suttle et al., 2004; Ramos-Scharron and MacDonald, 2007). For macroinvertebrates, an increase in fine sediment deposition from roads will: decrease taxa richness and abundance; decrease the abundance and richness of sensitive taxa such as *Ephemeroptera*, *Plecoptera*, and *Tricoptera*; and increase the number of oligochaetes and burrowing chironomids (Waters, 1995). These macroinvertebrate changes will adversely affect the amount and type of prey available to high-value fisheries. Large increases in fine sediment and substrate embeddedness can adversely affect spawning and rearing habitat, decrease juvenile fish growth, and feeding efficiency (Everest et al., 1987; Suttle et al., 2004).

3.2. Sediment Delivery from Road-Related Landslides

The downstream delivery of road-induced landslides is dependent on their location relative to the channel network, road design, and the travel distance of the failure (MacDonald and Coe, 2007). Road-failures initiated in colluvial hollows have a higher likelihood of delivering sediment to the channel network because these areas are located directly above first-order channels (Figure 6). Similarly, road-related failures in inner gorge landforms have a high probability of delivering sediment to streams because these areas are typically very steep and the slopes feed directly into the stream channels that carved these features (MacDonald and Coe, 2007). Landslides from roads crossing steep midslopes also are likely to deliver sediment to the channel network because hillslopes are steep, roads frequently cross low-order channels, and there is a high potential for intercepting subsurface (Wemple et al., 2001). Sediment delivery is also high when flood flows overtop road-channel crossings and initiate landslides on the fillslopes at a crossing (Furniss et al., 1998) (Figure 7).

Figure 6. Road-induced debris flows in northwest Washington state, USA. The debris flows initiated in the colluvial hollows on the upper road were triggered by road runoff, and these triggered the failures at the road-stream crossings on the lower road. This sequence has been defined as a "disturbance cascade" (Wemple et al., 2001). The road was built prior to the implementation of best management practices and large fill volumes were placed within colluvial hollow and inner gorge landforms (WA DNR, 1983).

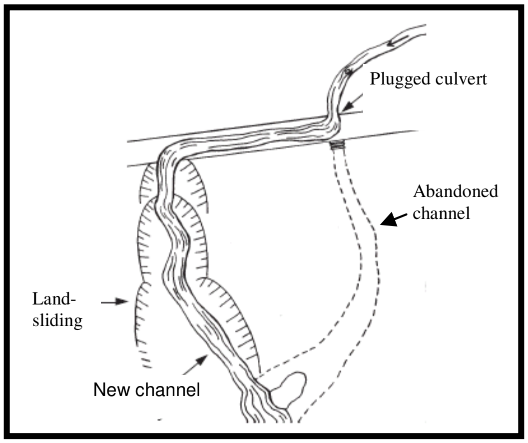

Figure 7. Schematic showing how a plugged culvert or other crossing failure can cause severe erosion by diverting water onto a road. When this water leaves the road it can cause gullying and/or landslides. Culvert failures due to overtopping or plugging with sediment and woody debris are common when the culvert diameter is less than the active channel width, the culvert is not set to the stream grade, or the culvert is poorly aligned with the stream channel (taken from Keller and Sherar, 2003).

The delivery of sediment from road-related landslides also depends on the road design. Sediment from cutslope landslides is more likely to be delivered to the stream network if the sediment is deposited into an inside ditch it than on the road travelway (Wemple et al., 2001). Fillslope slides have a much higher likelihood of delivering sediment to the channel network, and in the western U.S. 50% of the fillslope slides delivered sediment to the channel network after a large flood event (30-100 year recurrence interval). Fillslope slides are also more likely to initiate debris flows than cutslope slides (Wemple et al. 2001), and debris flows almost always deliver sediment into the channel network (MacDonald and Coe, 2007).

Road-induced landslides deliver both fine and coarse sediment (i.e., >2 mm) to the channel network. The episodic delivery of this sediment can induce debris flows, debris fans, valley terrace formation, channel avulsion, increased bedload transport, channel aggradation, substrate fining, channel widening, and pool infilling (MacDonald and Coe, 2007). These sediment-induced changes in channel morphology can increase downstream flooding and bank erosion by reducing the channel capacity, and also can adversely affect water quality and fish habitat (MacDonald and Coe, 2007).

In summary, roads not only induce landslides at a very high rate relative to forests or clearcuts, but they also have a greater potential to deliver this sediment to the stream network. In the Oregon Coast Range in the western USA, road-induced mass failures traveled on average three times farther than the mass failures in a mature forest. The combination of a much higher mass-failure rate and a higher sediment delivery means that road-induced mass failures can increase the amount of sediment being delivered to the channel network by nearly five times relative to mature forests (May, 2002).

4. Management Implications

The effective mitigation of road-related sediment production and delivery is dependent upon the dominant road erosion process and the proper selection and implementation of best management practices (BMPs). Without sufficient knowledge of the relevant road erosion processes, managers are more likely to treat the symptoms rather than the underlying cause.

Road surface sediment production can be reduced by improving road drainage, as this will decrease the amount of accumulated runoff and the erosive force applied to the road prism. Road drainage can be improved by increasing the frequency of road drainage structures such as waterbars, rolling dips, or cross-relief culverts. Guidelines for the spacing of drainage structures are typically based on the erodibility of the soil and the gradient of the travelway, with drainage spacing decreasing when travelway gradient and soil erodibility increases (Figure 8). Empirical regional spacing guidelines can be developed by observing the length and gradient of road necessary to initiate rill erosion (Figure 8), as sediment production increases significantly when the dominant surface erosion process transitions from rainsplash and sheetwash to rill erosion. Outsloping the travelway at a gradient of 3-5% towards the fillslope will further decrease the flowpath length and help minimize sediment production.

Surface erosion from roads also can be minimized by increasing the resistance of the road prism to the erosive forces of rainsplash and overland flow. Rocking the travelway can reduce sediment production by more than an order of magnitude (Coe,

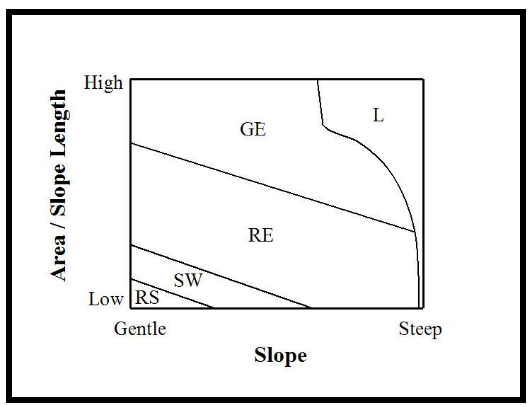

Figure 8. Conceptual process domains for rainsplash erosion (RS), sheetwash erosion (SW), rill erosion (RE), gully erosion (GE), and landsliding (L) as a function of flowpath slope gradient and the amount of runoff as a function or flowpath area or length. The effectiveness of BMPs can be maximized through knowledge of these process domains.

2006). The addition of groundcover (e.g. mulching) to cutslopes and fillslopes have proven to be effective in decreasing sediment production (Megahan et al., 1991; Megahan et al., 2001). Placing energy dissipators such as rocks or logging slash below road drainage outlets can greatly reduce surface erosion on the fillslopes. Grading of the road travelway should be minimized, and the need for grading can be avoided if adequate drainage is put in place and wet weather driving is restricted. Grading of inboard ditches also should be avoided unless absolutely necessary.

The same concepts can be applied to reduce the delivery of road surface erosion to the channel network. The delivery of road surface erosion is best prevented by draining the road travelway frequently before road-stream crossings (i.e., disconnecting). Rocking the remaining portion of the travelway that drains directly to the road-stream crossing will further minimize sediment delivery (Figure 9). Gully initiation below drainage outlets can be prevented by frequently draining the road and by placing energy dissipators below the outlets (Figure 9).

In areas dominated by road-related landsliding, road surface erosion may only represent 1-10% of total road-related sediment production (see Tables 1 and 2). In these instances priority should be given to avoiding road-related landsliding.

Many slope stability issues can be avoided during the road design phase by: 1) minimizing the length of road on steep and unstable hillslopes; 2) minimizing road width on steep midslopes; 3) minimizing the crossing of channels or convergent areas; and 4) laying out the road to fit hillslope topography (Sidle and Ochiai, 2006). Roads crossing slopes greater than 60-70% should be fully benched. If fill placement is necessary during construction, then the fill should be free of large organic material and should be compacted in successive layers of 0.2-0.3 m (Sidle and Ochiai, 2006).

On existing roads, fillslopes in excess of 70% should be removed or pulled back to a gradient of less than 70% (Benda et al., 1998). Priority should be given to treating steep fillslopes on roads adjacent to stream channels or roads crossing unstable landforms with a high likelihood of delivering sediment to the channel network (e.g., colluvial hollows, inner gorges). If fill removal is not feasible, then a retaining wall may be necessary to stabilize the fill. If cutslopes have undercut support for the upper hillslope then rock buttressing of the toeslope may be necessary (Chatwin, 1994).

It should be clear that improving road drainage is a critical to reducing preventing road-related landslides**.** Road runoff should not be drained onto unstable fillslopes or onto unstable areas such as colluvial hollows, inner gorges, or the scarps of deep-seated landslides. Outsloping can help to drain the road, but is generally not feasible when the travelway gradient exceeds 8-12%. In some cases road runoff has to be collected in an inside ditch so that the road runoff is not directed onto potentially unstable fillslopes or hillslopes. This will concentrate runoff and increase surface erosion in the ditch in exchange for reducing the likelihood of road-induced landslides.

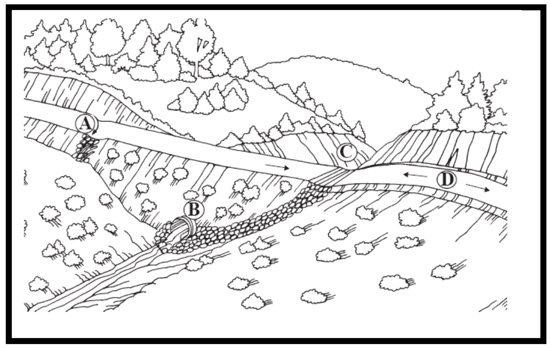

Figure 9. Schematic showing a road-stream crossing designed to minimize sediment delivery. Much of the road can be disconnected by draining the road runoff at point A. Armoring the fillslope at this point prevents gullying below the road. An armored dip at point C prevents fill erosion if the culvert (point B) becomes plugged and water flows across the road**.** Rocking the travelway should be rocked between points A and D will greatly reduce road surface erosion and the delivery of sediment to the stream (from Keller and Sherar, 2003).

Landsliding and gullying at road-stream crossings can be prevented by minimizing the potential for stream diversion. If possible, armored low water crossings should be used instead of culverts, as culverts can overtop or become plugged obstructed by sediment and debris during storm events. Culvert diameter should be greater or equal to the bankfull channel width so that culvert plugging is minimized (Cafferata et al., 2004). If the potential for stream diversion exists, an armored dip should be installed to route the diverted streamflow back into the channel (Figure 9).

The effective mitigation of road sediment impacts also will depend upon the resource of concern. For example, some aquatic species may be more sensitive to chronic rather than episodic erosion. In this case, priority should be given to minimizing road surface erosion, even though road-related landsliding may produce the most sediment. Due to the episodic nature of landsliding, improvements in resource conditions from landslide mitigation treatments may not be realized for years or decades.

5. Conclusions

Roads are important, chronic sources of runoff and sediment. This sediment is generated by both surface erosion and road-induced landslides. The surface erosion comes primarily from the road travelway as a result of rainsplash, sheetwash and rilling. Road surface erosion rates are highly variable, and depend on the contributing area, slope, precipitation intensity, soil type, soil rock content, and traffic. This sediment is delivered to the stream channel network primarily at road-stream crossings. Mean annual precipitation appears to be the primary control on road-stream connectivity.

Road-induced landslides can generate more sediment in some steep, humid areas than road surface erosion. An understanding of the process domains for road runoff and erosion is essential for reducing road sediment production and delivery. A range of best management practices have been developed to reduce road sediment production and delivery. In general it is easier to reduce road surface erosion than the number and size of road-induced landslides.

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