



## Hydrological processes and pathways affected by forest roads: what do we still need to learn?

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Forest roads are an important environmental issue. While many scientists interested in hydrology recognize climate-altering processes as an important global issue, there are problems that are similar in scope and magnitude because human industriousness has brought them to so many parts of the world. Almost everywhere people live and work they build and use unimproved roads, and wherever the roads go, a range of environmental issues follows. Among the environmental effects of unimproved roads, those on water quality and aquatic ecology are some of the most critical. Increased chronic sedimentation, in particular, can dramatically change the food web in affected streams, lakes, and oceans and reduces the effectiveness of drinking water treatment, which compounds problems of access to safe drinking water in developing regions. Low-standard roads accessing agricultural and forest lands comprise much of the extent of roads and probably affect the greatest area.

Effects of roads on sediment generation are closely tied to runoff generation and redistribution processes. The nearly impervious nature of road surfaces (or treads) makes them unique within forested environments and causes runoff generation even in mild rainfall events, leading to chronic fine sediment contributions of minor magnitude to water bodies. In some circumstances, much greater volumes of runoff can be generated by cutslopes, which may play an important role in more severe erosion processes. Lateral redistribution of runoff generated by roads (lateral to the natural hillslope) can greatly affect slope stability and peak discharges of small streams (Montgomery, 1994; Jones and Grant, 1996; Wemple *et al.*, 1996; Thomas and Megahan, 1998; Croke and Mockler, 2001).

If we look at the issue of what we need to learn or the research priorities for forest road hydrology, I would argue that the areas of cutslope hydrology and effectiveness of restoration efforts are perhaps most critical. I base this on the idea that research priorities hinge on the uncertainty exposed in existing research and the influence of that uncertainty on future decisions and designs. A great deal of literature on forest roads focuses on the road tread because of the obvious contrast with surrounding forest lands. They are described as almost ideal surfaces for infiltration excess (Horton) overland flow, with a narrow range of hydraulic conductivities (Reid and Dunne, 1984; Flerchinger and Watts, 1987; Luce and Cundy, 1994; Luce, 1997; Ziegler and Giambelluca, 1997; Croke *et al.*,

1999). It should be added that there is little we can do to change road tread hydrology; the impervious nature of the road tread is critical to its function, as water in the subgrade can weaken a road and make it impassable. There is neither much uncertainty in the issue, nor much opportunity to influence design. Perhaps the issue with greatest need for research on road treads is how to decompact them better once they are no longer in use. Decompacting roads is one method of mitigating the environmental effects of roads.

In contrast, the brief published record on cutslope interception belies the complexity of the subject and suggests a more substantial variability. Various researchers have observed that cutslope contributions can be much smaller than, comparable to, or much greater than road surface contributions; unfortunately, the dependencies are not clear. At a few sites in the mountains of Idaho and Oregon (USA) a substantial portion of the road runoff (80–95%) came from subsurface flow intercepted by the cutslope (Burroughs *et al.*, 1972; Megahan, 1972; Wemple, 1998). The conceptual model developed to explain the results of these studies is that interception occurs when a seasonally high water table flowing over an impermeable base (e.g. bedrock) becomes deep enough to intersect the road ditch. Thus the fraction of the permeable soil occupied by the road cut becomes a controlling factor in the amount of interception. This model has been broadly applied to study the effect of forest roads on watershed hydrology (La Marche and Lettenmaier, 2001; Tague and Band, 2001; Wigmosta and Perkins, 2001). Observations in Thailand showed nearly no cutslope contribution (Ziegler *et al.*, 2001). Personal observations from the Oregon Coast Range show that some roads intercept subsurface flow even when the water table is below the road, although in volumes closer to 40 to 50% of the total road runoff. On the Coast Range cutslopes, seepage occurs about 1–2 m from the top of the cutslope on a 5 m cutslope. This behaviour would indicate either the formation of a temporary perched water table or lateral unsaturated flow (e.g. Zaslavsky and Rogowski, 1969; McCord *et al.*, 1991; Jackson, 1992). The differences in behaviour are probably a function of climate and soil differences. For example, snowmelt is a large part of the soil

water input for the first three studies and a very minor fraction for Thailand and the Oregon Coast Range. The suggestion is that there may be benefit in repeating these studies in diverse climates and soils to characterize better how weather and soil properties control hillslope hydrology and subsurface flow interception by roads.

Soil and climate influences represent one level of context; at another, we need to understand the relative behaviour of roads in topographic landscape elements like swales, planar hillslopes, and ridges. We know that concave areas, where flow is concentrated, move most of the water in humid landscapes, but on roads there is some relationship between cutslope height and concavity, so that cutslopes are highest on ridges (where soils incidentally are shallowest) and cutslopes are lowest in swales. Where does most of the interception take place, in swales or on ridges? The answer is vitally important when considering the effects of interception and ensuing lateral redistribution on peak flows or slope stability. If most of the water is intercepted in swales, we could dramatically reduce risks of peak flow increases and slope instability by providing adequate drainage at all swale crossings. We can expect that the answer will change in differing soils and climates.

Climatic influences imply important temporal variability in road runoff generation processes. At subannual time scales, some regions experience seasonal changes between snowmelt and convective storm inputs, which can dramatically change the roles of cutslopes relative to road surfaces. At longer time scales we must consider the effect of storm size. Though many segments of road may not experience interception during typical events, more of the landscape may have higher water tables, and interception may be more spatially extensive during extended, severe weather events. This suggests that road interception effects on peak flows would be greatest during the wettest periods. However, Jones and Grant (1996) and Thomas and Megahan (1998) noted that the increases in basin peak flows that could potentially be attributed to roads were during relatively common storms (once every few years to several times per year). Resolving this apparent paradox will require improved understanding of the physics of road interception.

A key question to answer is: How does the hillslope respond during rare events compared with common events and how does this play out when roads are cut into the hillslope?

Roads simultaneously present challenges for the discipline of hillslope hydrology and opportunities for advancement. At a recent international conference on the topic a few scientists made a call to dissect hillslopes to get a better understanding of the medium that water flows through. When one realizes that roads represent an extensive set of dissections through many landscapes, a world of opportunity is revealed. Roads present opportunities to carry out the further detailed trench hydrology experiments, such as those at Maimai (Woods and Rowe, 1996) and Panola (Burns *et al.*, 2001), that are required to answer questions about fine-scale spatial patterns and process. Roads further provide the opportunity to leverage these detailed single site studies with less intensive measurements from a broad sample of hillslopes (trenches) in the surrounding area. Such an approach would be helpful in generalizing from more intensively monitored sites. At the very least, the long continuous transects provide opportunities to characterize differences in soil development, and soil thickness in different parts of the landscape providing context to measurements from one hillslope element (e.g. figure 2 in Dunne (1998)). Isotopes and other tracers would be useful in interpreting hydrometric data on multiple lightly instrumented road sections to quantify better the water flow sources, pathways, and residence times (Burns *et al.*, 1998; Kendall and McDonnell, 1998).

Forest roads are a difficult and pressing environmental challenge in many environments around the world. Their hydrologic behaviour is key to their off-site effects. Current models and literature addressing road hydrology are based on the hydrology of a few sites, and a more general conceptualization is needed. Observations in diverse environments taking advantage of the subsurface exposures provided by road cuts will be essential to developing and revising conceptualizations. Though roads present very specific problems in the field of hillslope hydrology, they also represent a great opportunity to advance the science while solving important environmental problems.

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