

INTRODUCTION TO SPECIAL ISSUE ON HYDROLOGIC AND GEOMORPHIC EFFECTS OF FOREST ROADS

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Roads have been a part of human landscapes for more than 40 centuries. During the 20th century, technological advances have increased our ability to construct new roads at unprecedented rates and into steeper terrain. In the last half of that century, an extensive network of roads has been constructed in forests and other wildlands to facilitate use and management of natural resources. They are the transportation system that allows transport of timber and minerals from forests and access for recreationists, land managers, fire fighters, and residents of villages or vacation homes.

Unfortunately, forest road construction may result in adverse changes to the environment. Roads fragment terrestrial and aquatic ecosystems by acting as a barrier to movement of some animals and plants. Roads can act as transportation corridors for plants, animals and fungi, some desirable, some not. Roads also affect the movement of water and sediment through landscapes. The combination of effects can be detrimental to native terrestrial and aquatic organisms, and negative correlations between road density and fish stocks have been noted (Lee *et al.*, 1997; Thompson and Lee, 2000).

The linear nature of roads and their tendency to run across topographic gradients yield an influence on watershed scale hydrologic processes that is much greater than one might expect from the small fraction of the land area they occupy. The concentration of runoff from nearly impervious road surfaces and intercepted subsurface flow into ditches effectively increases the drainage density, shifting the distribution of water on hillslopes and potentially increasing peak flows of streams. When there are few drainage features along roads there can be substantial inter-basin transfers of water between first-order streams. The effect is exacerbated when stream crossing culverts are plugged by debris, diverting a stream to other places in the landscape such as other streams or previously unchannelled hillslopes.

These hydrologic effects are partially responsible for changes to geomorphic processes and sediment budgets in roaded basins. Runoff from the road tread and intercepted subsurface flow contribute to surface erosion from soil bared by road construction, use and maintenance. Lateral concentration of water collected along the length of the road and discharged at ditch relief or stream crossing culverts increases the risk of landslides, gullies and destabilization of existing stream channels. Diversion of water from stream channels onto hillslopes or into other stream channels occurs more rarely but with greater consequence.

The papers in this special issue address many of the hydrologic and geomorphic issues identified above and contain important advances in the fields of hydrology and geomorphology on the subjects of hydrologic modelling, surface erosion and landscape evolution. They examine how the flowpaths of water are altered by the presence of roads and how these changes in flowpaths change geomorphic processes. Many of the efforts were spurred by recent work using digital elevation models (DEMs) to improve modelling of basin hydrology and landscape evolution. In a sense, roads are an experiment on the landscape; by perturbing the topography, we can view changes in the spatial patterns in hydrologic and geomorphic processes caused by roads, allowing us to test the principles derived in the earlier studies.

Two papers primarily address hydrologic issues. They examine changes in flood frequency following road construction using distributed hydrologic models. Because stream flows are affected by both roads and harvest areas, which are created within a short time of one another, it is difficult to derive statistically the independent effect of roads and harvest from stream gauge data alone (Jones and Grant, 1996; Thomas and

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Megahan, 1998). If the gauge data are used to calibrate a physically based model, the effects of harvest and roads can be introduced independently in the model. LaMarche and Lettenmaier used a grid-based model, while Tague and Band used a patch model, where a patch may be composed of many grid elements. Within-patch water routing was done using concepts from TOPMODEL (Beven and Kirkby, 1979) and inter-patch routing was similar to LaMarche and Lettenmaier's. LaMarche and Lettenmaier note a modest change in basin outflow from roading, and Tague and Band noted a lesser change. Tague and Band also modelled a large decrease in available water immediately below roads because of decreased inflow of water from upslope areas, and noted the potential ecological significance. These differences in results are consistent with the differences in the modelling approaches and suggest opportunities for observation-based comparisons between large scale and fine scale modelling of human alteration to hydrologic processes.

Four papers address the subject of road surface erosion. Two are published in this issue and two are published in the next regular issue of *Earth Surface Processes and Landforms* as a continuation of the special issue. These four papers examine subjects that have not seen substantial previous exposure in road erosion literature, such as spatial heterogeneity within a road segment or cutslope, describing temporal patterns in sediment availability, and comparisons between multiple studies. The findings are helpful to the understanding of surface erosion processes in any environment, not just forest roads. Megahan, Wilson and Monsen (this issue) examine erosion on granitic cutslopes over time as a function of site characteristics, weather and erosion control treatment. Their suggestions about how spatial variability in cutslope properties affects total cutslope sediment production are a rare acknowledgement of the importance of heterogeneity within a unit of observation. Fransen, Phillips and Fahey (this issue) review several road erosion studies in New Zealand and provide some synthesis on the differences in erosion caused by soil and climate differences. Ziegler, Sutherland and Giambelluca (next issue) study road erosion on unpaved roads in Thailand. They followed changes in the availability of erodible material over time as a function of maintenance, traffic levels and timing of traffic relative to precipitation. MacDonald, Sampson and Anderson (next issue) measured erosion and runoff from vegetated hillslopes, cutslopes, road running surfaces and complete road segments in the US Virgin Islands. Their objectives were to compare runoff and sediment production for storm events and gain a better understanding of runoff and sediment production from unpaved roads. Collectively the four papers highlight the complexity of the road surface erosion problem. Some of the controls on surface erosion from roads mentioned in these papers include soil or parent material texture, precipitation depth, form (snow or rain) and intensity, traffic history during dry and wet conditions, time following maintenance operations on road surfaces and cutslopes, erosion control treatments, flowpaths in ditches or on the road surface, and the amount of water intercepted by cutslopes.

Only one paper in the special issue discusses effectiveness of reclamation or restoration activities applied to roads. To reduce the effects of roads on geomorphic processes, many public land managing agencies in the United States are emphasizing 'removal' of roads delivering sediment to streams. Published examinations of the effectiveness of such activities are rare (e.g. Luce, 1997). Madej adds a substantial contribution to the field in a retrospective examination of practices in Redwood National Park in coastal northern California. She documents substantial reduction in risks of stream crossing failure and substantial reductions in erosion following restoration activities, and, importantly, notes that the relative success of restoration activities depends on the hillslope position. Projects low on hillslopes (closer to streams) had a greater likelihood of eroding substantially following treatment. It is an important reminder that the setting of a road within the watershed determines in part how it generates and delivers runoff and sediment.

The remaining three papers carry this message further and discuss roads within their context in the watershed (catchment area in UK terminology), touching on the issues of connectivity and interactions between roads and existing processes in watersheds. Wemple, Swanson and Jones consider the concept of a sediment budget for roads. While they note that overall, more sediment is generated by roads than captured by them, the pattern changes with hillslope position and process. They also discuss the idea that events initiated high in the watershed can set off a chain of events on roads lower in the watershed. Croke and Mockler examine initiation of gullies below roads following the ideas of Montgomery (1994) and Wemple *et al.* (1996). Culverts with long contributing lengths of roads and discharging to steep hillslopes had the greatest

likelihood of generating gullies connecting the road hydrologically to the stream network. In their study area, most gullies occurred below midslope roads because ridgetop roads had a greater frequency of drains and lower gradients at discharge sites. LaMarche and Lettenmaier (this issue) also briefly reported on the subject of hydrologic connectivity and suggest that hillslope curvature below the road is an important contributing factor to hydrologic connection and potential gully formation, adding an important new idea to the other studies. Florsheim, Mount and Rutten looked upslope from the roads to note that incision above stream crossing culverts can be a substantial source of sediment in itself and increase the connection of tributary streams to larger streams and rivers. Roads are frequently constructed along relatively large (fourth and higher order) streams to take advantage of low slopes on floodplains or alluvial fans. Placement of culverts below existing stream beds of small tributary streams crossing these features may create a knickpoint that migrates upstream, incising the channel, and eventually bypassing the sediment and water storage function of floodplains and alluvial fans. Collectively these papers advance understanding useful to landscape evolution modelling by examining thresholds for channel initiation, examining how geomorphic processes change down the slope in response to upslope geomorphic processes, and examining initiation and effects of knickpoints in alluvial fans.

One common feature of the studies in this issue is their basis in simple inventories and inexpensive measurements. A DEM and a geographic inventory of road characteristics and drainage allow application of many of the ideas presented in these papers. Measurements of erosion from roads in catch basins or behind silt fences may provide additional information, increasing precision of quantification. Given these simple data, these papers provide guidance on analyses that can be used to better plan and design forest roads.

Roads have been and will continue to be important corridors for travel, communication, and transport of goods. Their effects on the movement of water and sediment in forested landscapes are complex and sometimes pronounced. A thorough picture of the hydrologic and geomorphic processes affected by roads is useful for good design and maintenance of road networks. We hope that this special issue provides useful concepts and tools to professionals in charge of watershed protection and serves as reference and inspiration to researchers hoping to further advance our understanding of hydrologic and geomorphic processes in forest ecosystems.

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