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Evaluating the influence of forest roads on shallow landsliding

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Abstract

This study investigates how subsurface flowpaths are altered by forest roads and how these changes influence shallow landsliding susceptibility in steep, forested landscape. A simple conceptual model of the effect of forest roads on hillslope subsurface flow is developed. The model is incorporated into a hydro-geomechanical, threshold-based model for slope instability. In the model, the occurrence of shallow landsliding is evaluated in terms of drainage areas, ground slope and soil properties (i.e., hydraulic conductivity, bulk density, and friction angle). Model results allow to quantify the influence of roads on shallow landsliding hazard across a landscape and to generate hypotheses about the broader geomorphic effect of roads.

Modelling results are compared with field data collected in four sites located in north-eastern Italy. Observed landslide patterns are broadly consistent with model estimates, a finding that underscores the utility of this simple approach for predicting the geomorphic effects of forest roads constructed on steep slopes. The approach used in this study may be useful for defining criteria for road design that reduce the effects of roads on geomorphic processes.

Keywords: Anthropogenic effects; Runoff and streamflow; Forest roads; Shallow landsliding; Subsurface Flow; Hillslope hydrology

1. Introduction

The interaction between forest roads and geomorphic processes lies at the heart of several key issues concerning the effects of roads on the environment. Geomorphic effects of forest roads range from chronic and long-term contributions of fine sediment into stream to catastrophic effects associated to shallow landsliding during large storms. In steep, forested terrain prone to landsliding, the greatest effect of roads on erosion rates is from increased rates of mass soil movement after road building (Gucinski et al., 2001). Major issues motivating concern about road-related erosion include potential degradation of aquatic habitat and water quality (Harr and Nichols, 1993) and risks to public safety and structures downstream (Burroughs, 1985; Pozzatti and Cerato, 1984).

The magnitude of road-related mass erosion differs with climate, geology, topography, road age, construction practices and storm history (Gucinski et al., 2001). Several inventories have been conducted to assess road effects on mass failures, with more specific fo-

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cus on U.S. Pacific Northwest and New Zealand (Sidle et al., 1985; Swanson and Dyrness, 1975; Reid, 1981; Mosley, 1980; Coker and Fahey, 1993), each documenting increased rates of landsliding in road areas relative to unmanaged forested areas. Sidle et al. (1985) documented accelerated erosion rates from roads because of debris slides ranging from 30 to 300 times the forest rate.

Influence of forest roads on geomorphic processes generally results from concentration of both runoff generated as overland flow from compacted road surfaces and intercepted subsurface flow by road cutslopes (Megahan, 1972; Anderson, 1983; Reid and Dunne, 1984; Luce and Cundy, 1994; Montgomery, 1994; Ziegler and Giambelluca, 1997; Luce and Black, 1999; Wemple et al., 2001). Subsurface storm flow dominates runoff generation in steep soil-mantled terrain where precipitation infiltrates and flows laterally either through macropores or over a lower conductivity zone. In these environments, road interception occurs when a seasonally high water table flowing over on 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. Subsurface flow intercepted along the road cut may be diverted to surface runoff, and then redirected downslope, modifying pre-existing flow paths on the hillslope. In steep, soil-mantled terrain, the combination of ubiquitous subsurface flow and of the interception by road cuts yields an influence on hydrogeomorphic processes that may be much greater than one might expect from the small fraction of the land area roads occupy (Luce and Wemple, 2001).

Road-generated runoff is usually routed by roadside ditches and therefore concentrated in particular areas below the road. The effect of this concentration of flow will depend on the characteristics of the receiving areas. When the road drainage is not connected to the stream network (at least through surface flow), road runoff may either reinfiltrate into the unchanneled terrain, or reinfiltrate below a gully that does not extend to the stream network. In these cases, concentrated road runoff may affect shallow landsliding potential in the receiving areas and decrease the critical source area required to initiate headwater streams (Montgomery, 1994). In cases where the road network is connected to the stream network road, runoff may enter a stream directly at a stream crossing culvert, or enter a stream indirectly through the formation of a gully, extending to the river network, below a ditch relief culvert. Therefore, the collective contribution of intercepted hillslopes to the road and the road surface drainage features determine the road impact on mass wasting on hillsides downslope. This impact may be large when roads intercept large amounts of subsurface flow and redirect it to unchanneled terrain, conditionally unstable, below the road.

The purpose of this work is to gain further insight on road interactions with hillslope flow paths and on how these interactions influence shallow landsliding of concerned hillslopes. This paper addresses these issues by developing a conceptual and quantitative framework for evaluating how roads in different landscape positions (valley bottom, midslope, ridgetop) affect subsurface flow paths and associated mass failures. A threshold-based model for slope instability (Dietrich et al., 1993; Montgomery and Dietrich, 1994; Borga et al., 1998, 2002a) is extended to the case of hillslopes interested by road networks. A range of scenarios is used to generate hypotheses about the effects of road on hillslope stability. Simulation results are also compared with available field data collected in north-eastern Italy in order to assess how well the model captures the processes of interest.

2. A conceptual model of cutslope interception, throughflow rerouting and slope instability

The conceptual model of cutslope interception and throughflow rerouting used in this study is based on coupling of digital topography with a simple model of steady-state rainfall-runoff to calculate the saturation deficit at any point in the landscape. The following assumptions are used to model the subsurface flow propagation:

- Shallow lateral subsurface flow follows topographic gradient.
- The entire soil profile is initially wet to field capacity.
- Lateral discharge at each point is in equilibrium with a steady-state recharge R [LT^{-1}], i.e. the infiltrating rainfall which passes through (or bypasses) the unsaturated zone to reach the saturated zone and eventually becomes subsurface runoff. The steady-state