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Effects of vegetation cover and road-concentrated flow on hillslope erosion in rainfall and scouring simulation tests in the Three Gorges Reservoir Area, China

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ABSTRACT

Roads play a significant role in altering hydrological processes. Roads cause more erosion to be generated from the hillslope for both road-concentrated flow and rainfall. In this study, six treatments (Natural Restoration, Grass, Grass & Shrub, Sodded Strip, Grass & Farmland, and Farmland) were used to recolonize hillslope plants on a newly built unpaved road. Rainfall simulation (rainfall intensity of 90 mm h^{-1} and 120 mm h^{-1}) and scouring simulation (scouring flow rate 15 L min^{-1} and 20 L min^{-1}) tests were conducted to identify the effects of plants on soil erosion. In the rainfall simulation test, Grass & Shrub was more effective at reducing hillslope erosion than the other treatments, and Grass & Shrub also had a lower runoff coefficient, soil detachment rate, and higher efficiency in trapping runoff and sediment. The hydrological responses of all of the tested plots in the scouring test were much faster than in the rainfall simulation, as indicated by the lower lag time to runoff generation. The hillslope erosion in the scouring test was significantly higher than in the rainfall simulation. The water-stable aggregate, saturated hydraulic conductivity, vegetation cover, root length density, and root weight density were important factors that conditioned the runoff generation and sediment yield from the hillslope in both experimental tests. In the scouring test, in infiltration improvement and flow erosivity reduction, Grass was more effective at trapping runoff and sediment because of its dense well-developed system of fine roots. Therefore, except for an immediate surface cover, in the areas where the hillslope has a risk of road-concentrated flow scouring, the enhancement of topsoil roughness was also very important in weakening the impact of road-concentrated flow on the hillslope.

1. Introduction

The environmental impacts of roads are a serious problem worldwide, such as eastern Spain (Arnáez et al., 2004; Cerdá, 2007), northern Thailand (Ziegler and Giambelluca, 1997; Ziegler et al., 2000, 2001), northwestern America (Foltz et al., 2009; Luce and Black, 1999; Wemple et al., 2001) and the Loess Plateau of China (Cao et al., 2006). Much attention has been paid to the problem through both research and management in recent decades.

Road construction significantly alters hydrologic and geomorphic processes. The roles of the road in hillslope hydrological processes include the interception of the upslope surface flow and the sub-surface flow and transforming these flows into road surface runoff under certain conditions (Megahan and Clayton, 1983; Negishi et al., 2008); the quick response of the road surface to rainfall, the large quantity of runoff generation even in small rainfall events (Ziegler and Giambelluca, 1997) for high compaction, and the runoff generated from the road surface are important sources of Horton overland flow (Ziegler et al., 2001).

The hydrologic changes made by the road caused faster timing and a higher magnitude of peak streamflow (King and Tennyson, 1984; Jones and Grant, 1996). However, under certain conditions, the hydrological connectivity between the road runoff sources and stream networks was limited, and the hydrological connectivity determined the efficiency of the runoff concentrated on the road to the stream via drainage outlets (Croke and Mockler, 2001). Lane et al. (2006) summarized the destinations of the road-concentrated runoff and noted that the gully that formed below the drainage outlet on the hillslope was the dominant passway. Once a gully is formed, the soil loss increases exponentially (Valentin et al., 2005). Montgomery (1994) found that the main causes for gully formation on the hillslope after road building were overland flow concentration by the road and artificial drains. Wemple et al.'s (2001) investigation in Oregon concluded that debris sliding from mobilized road hillslope was the dominant source of sediment yield from the road. Some techniques therefore must be used to spread

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the concentrated runoff in space and time and to increase the in situ infiltration capability instead of directing it straight to the unprotected hillslope (Nyssen et al., 2002).

However, little attention had been given to the off-site impact of the road-concentrated flow on road hillslope erosion processes, especially on the low-volume unpaved road, and the emphasis of erosion-controlling management on the hillslope usually focuses on rainfall erosion reduction. Where there is a drainage outlet, the destructive power of the concentrated flow is much greater than rain.

The hillslope was usually formed by excavated material originally from the cutslope or road surface during construction in the sloping terrain and is characterized by litter compaction and high infiltration. The loss of the structure of the hillslope indicates litter soil loss compared with cutslope and road surface in small rainfall events but is much more erodible when exposed to the concentrated flow due to the poor anti-erodibility and soil strength failure of the topsoil. Thus, vegetation recolonization is essential in road slope erosion control. Martínez-Zavala's (2008) research in southern Spain noted that increased plant cover of 30–40% was necessary to maintain road slope erosion at low levels, especially during the winter. Megahan et al. (2001) tested three erosion control treatments, including the dry seeding of grass, hydroseeding plus mulch and terracing with hydroseeding plus mulch, and found that dry seeding was more suitable in road slope reduction. However, treatments like hydroseeding and terracing were not applicable to low-volume unpaved roads due to their poor cost-effectiveness.

The Three Gorges Reservoir Area (TGRA), which lies on the upper Yangtze River in central-western China, is the world's largest artificial reservoir. In recent years, the landscape of the TGRA has changed greatly because of the Three Gorges Project, countryside migration, tourism development and rural construction. The implementations of the project caused the rapid expansion of the unpaved road network. In contrast to the rapid development of road construction, management and basic research were greatly lagging. Soil erosion increased by road construction has become a serious problem in the TGRA; therefore, highly cost-effective road erosion control treatments are urgently needed.

Supposed that the potential of road in runoff re-routing and flow concentrating, and the efficiencies of different hillslope re-vegetation models in erosion control were still unclear under rainfall and concentrated flow on the low-volume road. One of the objective of this study was to test the effectiveness of six treatments, Natural Restoration, Grass, Grass & Shrub, Sodded Strip, Farmland & Grass, and Farmland, in erosion reduction on a newly built unpaved low-volume road hillslope in the TGRA, another purpose was to find a cost-effective approach to resolve the erosion controlling of the low-volume road in the other regions of China or other counties. Rainfall simulation tests were carried out on the hillslope after eight months of plant growth during the first rainy season after road building. Then, scouring tests were used to simulate the road surface concentrated flow. Finally, rainfall simulation and scouring tests were carried out to identify the mechanisms of different treatments in hillslope erosion reduction under different experimental conditions.

2. Methods and materials

2.1. Study area

The TGRA covers areas of the Hubei and Chongqing province (Fig. 1). Three ongoing studies were conducted in the TGRA for road development and management: one in Hubei Province and two in Chongqing Province, respectively. In this study, the research area was located in Hubei Province. Before the study area was selected, eight watersheds that were randomly located in Hubei province were chosen to investigate their soil condition, plants, road information and land utilization. According to the investigations, the dominate plant species were similar, and the soil matrix was sand–shale. Orchards and tea gardens were widely distributed, and much of the unpaved low-volume roads were built among those lands. This study was conducted in Mozixi, one of the eight investigated watersheds, which is located 45 km southeast of Yichang City and covers 7.3 km^2. The area is in a northern subtropical continental monsoon climate zone and has a mean yearly temperature of 17 °C (Liu et al., 2014). The annual rainfall is 1217 mm, which primarily occurs from April to September (>80% of the total rainfall). The elevation ranges from 137 to 675 m. The purplish soil in this region is predominantly weathered from red sand–shale.

The road information investigation was conducted in August 2009. The road network in Mozixi was well developed with a road density of 9.24 km km^{-2}. However, low-volume roads constituted greater than 70% of the total road length in the watershed and included unpaved rural roads and grass roads that provided access for farmers and farming vehicles. Unpaved rural roads and grass roads were widespread and accounted for 49.2 km, with a 4.1-km concrete main road that zigzagged through the watershed to connect different villages

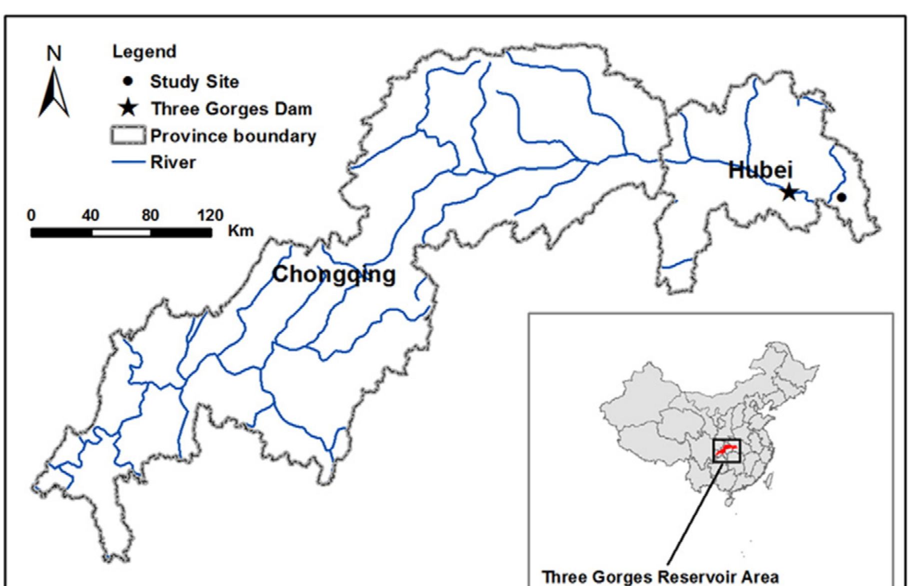

Fig. 1. Location of the Three Gorges Reservoir Area on a map of China. The Three Gorges Reservoir Area covers the Chongqing and Hubei Provinces. The study site is located in Hubei Province.