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# Hydrogeomorphic connectivity on roads crossing in rural headwaters and its effect on stream dynamics

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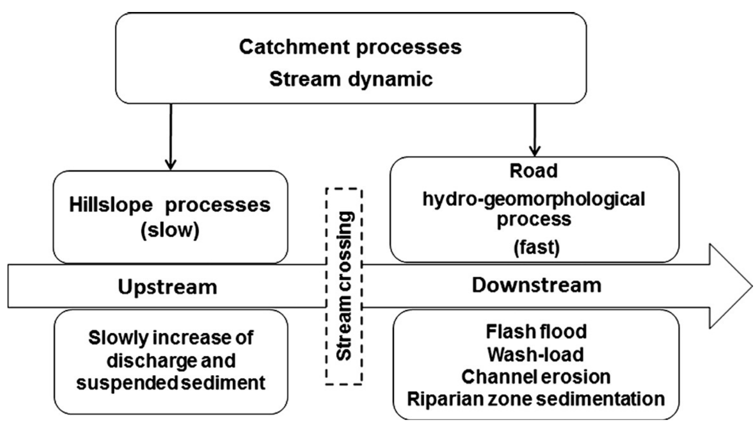
## HIGHLIGHTS

- Unpaved road increased significantly the sediment transfer into small stream.
- Discharge enhanced at lower magnitude compared with suspended sediment concentration.
- Stream exhibited a hybrid pattern controlled by hillslope and by road processes.
- Stream becomes responsive to rapid flood-wash load transfer due to stream-crossings.
- Riparian vegetation lost its functions in headwaters with stream-crossing connection.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Unpaved roads are ubiquitous features that have been transforming the landscape through human history. Unpaved roads affect the water and sediment pathways through a catchment and impacts the aquatic ecosystem. In this study, we describe the effect of unpaved road on the hydrogeomorphic connectivity at the rural headwater scale. Measurement was based on the stream crossing approach, i.e., road superimposing the drainage system. We installed a Parshall flume coupled with single-stage suspended sediment sampler at each stream crossing. In addition, we displayed our monitoring scheme with an upscaling perspective from second-order to third-order stream. We concluded that the road–stream coupling dramatically changed the stream dynamic. The increase of discharge caused by roads at the headwater was 50% larger compared to unaffected streams. Additionally, suspended sediment concentration enhancement at stream crossings ranged from to 413% at second-order streams to 145% at third-order streams. The landform characteristics associated with the road network produced an important hydrogeomorphic disruption in the landscape. As a result, the sediment filter function of the riparian zone was reduced dramatically. Therefore, we recommend that projects for aquatic system restoration or conservation in rural landscape consider the role of the road network on stream dynamics.



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## 1. Introduction

A road network passes over landforms such as mountains, hillslopes, valleys, fluvial terraces, and drainage systems. Roads cause landscape fragmentation and can affect biological systems (Forman et al., 2003). In addition, because of the linear nature of roads across the topography, roads affect the water and sediment dynamics (Jones et al., 2000; Wemple et al., 2001; Ramos-Scharrón and LaFevor, 2016), and stream habitats (Seutloali and Beckedahl, 2015; Maitland et al., 2016) along a watershed. However, strategy for road construction as ecological corridors i.e., to mitigate the impact of road construction on plant and animal habitats has been proposed (Cheng et al., 2015).

Roads are important for rural access, sustaining livelihoods, and reducing poverty. For this reason, it is expected that 1 to 2 million kilometers of road will be built every decade until 2050 (Faiz et al., 2012). However, roads and trails have been recognized for a long time as an important source of runoff and sediment, and they also play a major role as connector for sediment transfer into streams (Gilbert, 1917). Thus, roads have been ascribed both positive and negative effects. On one hand, roads are important for socioeconomic development, especially in developing countries (Faiz et al., 2012; Sidle and Ziegler, 2012). On the other hand, despite the small portion of the landscape occupied by roads, they cause several impacts on the geo-ecosystem such as changes in hydrogeomorphological processes, i.e., runoff generation, subsurface interception, sediment production, and sediment transfer into aquatic systems (Luce and Black, 1999; Ziegler et al., 2001a; b; Luce, 2002; Rijsdijk et al., 2007; Ramos Scharrón, 2010; Thomaz et al., 2014).

Roads can produce sediment from various features, i.e., cutslopes, roadbanks, roadbed, ditch, and fill slopes (Fu et al., 2010). Several studies have advanced our understanding of the controlling factors and mechanisms of runoff and sediment production, such as slope gradient, slope length, interstorm sediment preparation, roadbed surface curvature, road age, and road maintenance, particularly by rainfall simulation at the plot scale (Selkirk and Riley, 1996; Arnáez et al., 2004; Sheridan et al., 2008; Jordan-Lopez et al., 2009) and on road segments (Reid and Dunne, 1984; Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2007).

In addition, many studies have considered the effects of sediment transfer from road to river system, e.g., suspended sediment load, bedload, nutrient, and contaminants. Most of the present study involves application of the stream crossing ratio approach (Lane and Sheridan, 2002; Sheridan et al., 2006; Sheridan and Noske, 2007a; b; Purcell et al., 2011).

Road hydrogeomorphological studies are moving from empirical and physical-based studies concerning runoff and sediment generation at the plot and road-segment scale to sediment transfer studies at the stream-crossing level. However, a more integrative approach of sediment transfer at the catchment scale is needed (Egozi and Lekach, 2014). At the catchment scale, the complexities of sediment dynamics require controlling sediment routing in the fluvial system, and the monitoring of road-to-stream connectivity is crucial for improvement of modeling (Brierley et al., 2006; Fu et al., 2010).

Connectivity is an emergent concept in the environmental science, especially, in geomorphology, hydrology and ecology. Connectivity is related to the physical macro-connections between different parts of the catchment system such as hillslope and river channel (Brierley et al., 2006; Michaelides and Chappell, 2009; Baartman et al., 2013; Parsons et al., 2015). Moreover, road network, and overall man-made line (e.g., tracks, pathways) are one of the key human topographic signatures widespread across landscapes; which results in geomorphic and hydrologic processes change (Croke et al., 2005, Marchamalo et al., 2015; Tarolli and Sofia, 2015).

In the headwater region (~50 km$^2$), the stream hydrogeomorphological response is controlled particularly by hillslope processes (Knighton, 1998). Therefore, the headwater is a geomorphological system that is sensitive to land-use change, and the stream catchment dynamics are dependent on the slope–channel coupling (Egozi and Lekach, 2014). In addition, roads enhance hydrogeomorphological connectivity because roads increase the human-catchment system connection (Bracken and Croke, 2007; Egozi and Lekach, 2014; Latocha, 2014; Tarolli and Sofia, 2015).

Small streams (first- to third-order streams) are important for upscaling sediment transfer for the whole catchment (Bilby et al., 1989; Jolicoeur et al., 2007; Thomaz et al., 2014). Therefore, understanding the process of transport of road sediment through these systems is critical. Land that has been abandoned can cause a decrease in the effect of human disturbance pertaining to slope–channel coupling (Keesstra, 2007; Latocha, 2014). However, the hydrogeomorphic connectivity of an active road system with a rural headwater region and its effects on stream dynamics is still poorly understood. The objective of this study was to assess the effect of road–stream coupling on discharge and suspended sediment concentration and its effects on stream dynamics.

## 2. Materials and methods

### 2.1. Study area

A headwater study region with an area of ~2.5 km$^2$ within the Rio das Pedras watershed valley, Brazil, was chosen for this research (Fig. 1) because of its land use characteristics and its representative geomorphological context in the region. The land use is mostly forest cover and secondary forest as well as agriculture with important areas of pasture. This type of land use is representative of dissected terrain located within the Rio das Pedras watershed valley. The river is a source of the water supply to Guarapuava city, which has ~170 thousand inhabitants. Therefore, soil and water conservation is of utmost importance.

According to Köppen (1948), the climate in the study area is classified as mesothermic subtropical wet (Cfa). The annual temperature is 17–18 °C, rainfall ranges from 1800 to 2000 mm, and annual evapotranspiration is 900–1000 mm (Caviglione et al., 2000). The predominant effusive igneous rock is basalt, and the soil cover consist mainly Cambisols (IUSS Working Group WRB, 2006). The clay content of the soil ranges from 35% to more than 70%. The relief is formed predominantly by convex hillslopes, and approximately 75% of the area of the headwater region has slope between 12% and more than 30%. The land use (Table 1) is not diversified and forest cover, including riparian vegetation, is the major land use. Secondary forest and fallow agriculture is the second land use in the area, followed by pasture land.

### 2.2. Monitoring design

The monitoring design followed an upscale approach, i.e., a tributary trunk system with a second order stream connecting to a third order stream. This structure forms a longitudinal linkage and has implication on water transfer and sediment transfer or storage through the system (Brierley et al., 2006).

The monitoring site was formed by two different road features (Fig. 2a). First, a secondary road (Table 2) drained to stream crossing 1, i.e., 2ndUA and 2ndD, where Parshall flumes 1 and 2 were located, respectively (Fig. 2a). This road has major slope and contribution area and lesser roadbed cover gravel. In addition, it was covered by grass (~30%) in some roadbed sectors, indicating low traffic. Second, a main road drained to stream crossing 2, i.e., 3rd, where Parshall flume 4 was located (Fig. 2a). This road has lesser slope and contribution area and major roadbed cover of gravel.

Monitoring of unpaved rural road runoff and suspended sediment transfer into streams was carried out from 09/19/2012 to 09/29/2013, and 30 rainfall events with 324 sampling collections of flow rates and sediment concentration were registered. A single-stage suspended sediment sampler was used to automatically collect samples at the rising limb from a flashy stream (Gordon et al., 2004). Four sediment samplers