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Topographic controls on overland flow generation in a forest – An ensemble tree approach

Martin Loos [a,*], Helmut Elsenbeer [a,b]

[a] University of Potsdam, Institute of Earth and Environmental Sciences, Karl-Liebknecht-Strasse 24-25, 14476 Potsdam, Germany
[b] Smithsonian Tropical Research Institute, AP 0843-03092, Balboa, Ancon, Panama

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SUMMARY

Overland flow is an important hydrological pathway in many forests of the humid tropics. Its generation is subject to topographic controls at differing spatial scales. Our objective was to identify such controls on the occurrence of overland flow in a lowland tropical rainforest. To this end, we installed 95 overland flow detectors (OFDs) in four nested subcatchments of the Lutzito catchment on Barro Colorado Island, Panama, and monitored the frequency of overland flow occurrence during 18 rainfall events at each OFD location temporal frequency. For each such location, we derived three non-digital terrain attributes and 17 digital ones, of which 15 were based on Digital Elevation Models (DEMs) of three different resolutions. These attributes then served as input into a Random Forest ensemble tree model to elucidate the importance and partial and joint dependencies of topographic controls for overland flow occurrence.

Lutzito features a high median temporal frequency in overland flow occurrence of 0.421 among OFD locations. However, spatial temporal frequencies of overland flow occurrence vary strongly among these locations and the subcatchments of Lutzito catchment. This variability is best explained by (1) microtopography, (2) coarse terrain sloping and (3) various measures of distance-to-channel, with the contribution of all other terrain attributes being small. Microtopographic features such as concentrated flowlines and wash areas produce highest temporal frequencies, whereas the occurrence of overland flow drops sharply for flow distances and terrain sloping beyond certain threshold values.

Our study contributes to understanding both the spatial controls on overland flow generation and the limitations of terrain attributes for the spatially explicit prediction of overland flow frequencies.

1. Introduction

Overland flow constitutes an important hydrological pathway in various forested soilscapes. Several studies have established its relevance in tropical rainforests (e.g., Bonell and Gilmour, 1978; Elsenbeer and Lack, 1996; Elsenbeer, 2001; Godsey et al., 2004; Johnson et al., 2006) and in other forest ecosystems (e.g., Zehe et al., 2007; Gomi et al., 2008a,b). This hydrological relevance bears on ecosystem processes such as nutrient and carbon fluxes (Williams et al., 1997; Eddy et al., 1999; Grimaldi et al., 2004; Johnson et al., 2006; Chaves et al., 2009), sediment transport (Jansson and Stromberg, 2004; Sidle et al., 2006), and soil moisture patterns (Grayson et al., 1997).

Although the occurrence and relevance of overland flow in forests of the humid tropics and elsewhere have been documented, the precise nature of its controls and its spatial organization remains murky. Whereas changes in overland flow generation (OFG) resulting from land-use change have been confirmed (Zimmermann et al., 2006; Germer et al., 2010), only few studies have documented the spatially discontinuous and in places counter-intuitive occurrence of overland flow in undisturbed forested landscapes (Elsenbeer and Vertessy, 2000; Godsey et al., 2004; Germer et al., 2010). Attempts to explain such patterns had to rely on field observations (Godsey et al., 2004), or failed when relying on modeling combined with topography-based parameters such as the Topographic Wetness Index (TWI) (Vertessy and Elsenbeer, 1999; Kinner and Stallard, 2004). In both instances, return flow as a mechanism of OFG and microtopography were invoked to explain observed spatial patterns. However, an approach for the systematic investigation of various topographic controls on OFG and the quantification of their relative importance is still missing.

Such an approach appears overdue in view of the well-established usage of terrain attributes derived from Digital Elevation Models (DEMs) in research and land management (Moore et al., 1991). Beyond that, a deeper understanding of any links between OFG and terrain attributes is bound to increase our understanding of the sensitivity of overland flow-prone systems to anthropogenic disturbances (Bonell and Molicova, 2003; Thang and Chappell, 2004; Chappell et al., 2006a).

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* Corresponding author. Address: Dr. Gebauer Str. 40, 55411 Bingen, Germany. Tel.: +49 0767082120; fax: +49 331 977 2068.

E-mail address: martin.loos@alumni.uni-potsdam.de (M. Loos).

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Against this background, our objectives were to investigate terrain attributes for (1) their relative importance and (2) their partial dependency as explanatory variables for the occurrence of overland flow in a landscape modeling approach. In addition, we explored (3) the influence of spatial resolution on the predictive quality of terrain attributes as well as (4) the interaction of such attributes in explaining the occurrence of overland flow.

2. Methods

2.1. Study site

Being part of the Panama Canal Basin at Lake Gatun, Barro Colorado Island (BCI) houses the 10.1 ha Lutz Creek watershed, which has been extensively monitored since 1971 by the Environmental Science Program (ESP) of the Smithsonian Tropical Research Institute. The focus of the present study is on a subcatchment named Lutzito (Fig. 1).

Lutzito catchment encloses 3.5 ha of tropical semi-deciduous moist forest without any human disturbance for at least 100 years (Foster and Brokaw, 1982). Lutzito is drained by a fan-shaped drainage network (Fig. 2), consisting of distinct, in places gully-like incisions into the regolith, with a noticeably heterogeneous micro- and macrotopography. The latter is characterized by steep terrain, with slopes up to 45° and intermingled ridges and terraced positions. Slope lengths above channel heads range between 20 and 100 m. The catchment outlet itself is located on bare bedrock.

The geology of Lutzito consists of the tuffaceous siltstone of the Caimito Marine Facies (Woodring, 1958). Soils are generally shallow in depth (<50 cm) and categorized as Ferric Cambisols (FAO, 1998). Moreover, Godsey et al. (2004) revealed a decrease in saturated hydraulic soil conductivity from a median of 29.7 mm h^{-1} at a depth of 12.5 cm to a median of 1.4 mm h^{-1} at a depth of 30 cm below the soil surface.

Both Godsey et al. (2004) and Kinner and Stallard (2004) pointed at the prevalence of overland flow in Lutz Catchment, which coincides with observations of high rates of erosion and high runoff sediment loads during particular rainfall events. In addition, active pipe flow openings can be observed in Lutzito, mostly alongside channel banks and at some channel head locations.

BCI faces distinct seasonal variations in a broad range of meteorological characteristics. Of the mean annual precipitation of 2633 mm, an average of only 290 mm falls during the dry season starting mid-December and lasting until April or May (Paton, 2005). However, total rainfall amounts during wet season vary considerably among years and short spells of dry conditions are not unusual during the wet season. The dry-to-wet season transition affects the hydrological and ecological conditions within Lutzito catchment in many ways. For instance, soil moisture increases with the onset of the rainy season, as does runoff in Lutz Creek (Paton, 2005; Windsor, 1990). In contrast, leaf fall peaks early in the dry season and remains high for the rest of it (Haines and Foster, 1977).

2.2. Field sampling

Data on spatially explicit frequencies of overland flow generation were collected during the dry to wet season transition from mid-June to August 2005 for 18 rainfall events detailed in Table 1. For this purpose, a total of 95 overland flow detectors (OFDs) were spread within four subcatchments of Lutzito (specified as subA, subB, subC and subD). In each of them, 3–4 contour-parallel transects and the channel headwaters were equipped with a variable count of OFDs. Number and location of transects varied among subcatchments so as to cover topographic differences at the subcatchment scale, whereas the number, specific position and spacing between OFDs in each transect was varied to cover topographical heterogeneities within the individual transects. Thus, 23 OFDs were located inside sub-A, 20 OFDs inside sub-B, 30 OFDs inside sub-C and 22 OFDs inside sub-D (Fig. 2). OFDs consisted of 25 cm of perforated plastic pipe connected to a container for collecting surface runoff, which was checked for a response after each rainfall. OFD failures (0.4% of all OFD readouts) were omitted from further analysis. The position of each detector was mapped using a Global Positioning System (GPS) device (Trimble Asset Surveyor v. 5.00, Model TSC1).

The relative frequency of rainfalls for which a single OFD indicated overland flow is further on referred to as the temporal (i.e. time-aggregated) frequency of overland flow occurrence at a given OFD location. In contrast, the spatial frequency of overland flow occurrence signifies the fraction of OFDs which detected surface runoff during a single rainfall event.

Using a Hydrological Services tipping bucket rain gauge, precipitation was measured by the ESP in a clearing 280 m from the out-

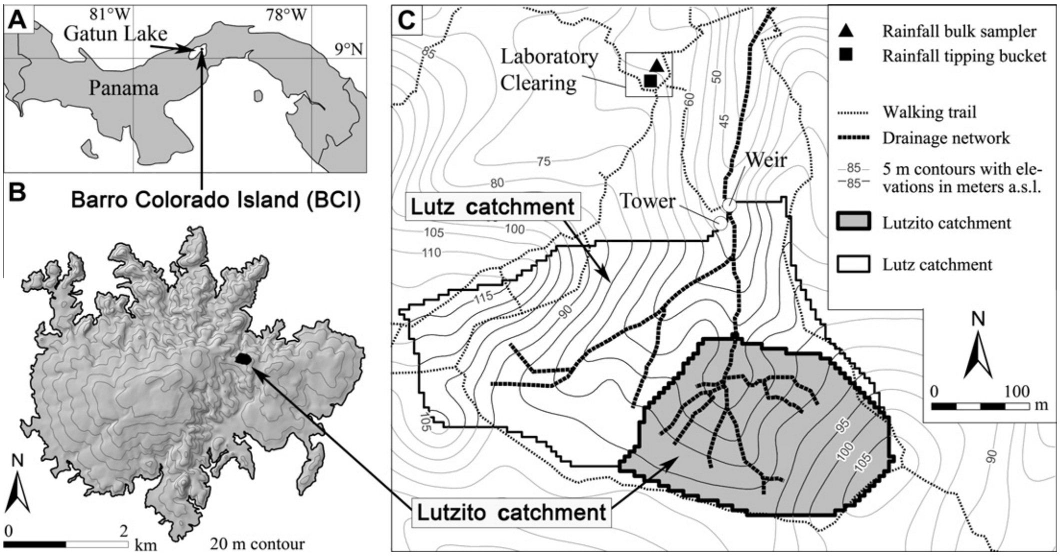

Fig. 1. (A) Map of Panama indicating the location of Barro Colorado Island (BCI) in Lake Gatun. (B) Location of Lutzito catchment on BCI, with 20-m contours. (C) Map of the Lutzito catchment study site as part of Lutz catchment area. All contouring based on the DEM by Kinner et al. (2002).