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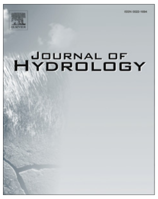

How do slope and surface roughness affect plot-scale overland flow connectivity?

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SUMMARY

Surface micro-topography and slope drive the hydrological response of plots through the gradual filling of depressions as well as the establishment of hydraulic connections between overflowing depressions. Therefore, quantifying and understanding the effects of surface roughness and slope on plot-scale overland flow connectivity is crucial to improve current hydrological modeling and runoff prediction. This study aimed at establishing predictive equations relating structural and functional connectivity indicators in function of slope and roughness. The Relative Surface Connection function (RSCf) was used as a functional connectivity indicator was applied. Three characteristic parameters were defined to characterize the RSCf: the surface initially connected to the outlet, the connectivity threshold and the maximum depression storage (DS_{max}). Gaussian surface elevation fields ($6\ m \times 6\ m$) were generated for a range of slopes and roughnesses (sill σ and range R of the variogram). A full factorial of 6 slopes (0–15%), 6 values of R (50–400 mm) and 6 values of σ (2–40 mm) was considered, and the RSCf calculated for 10 realizations of each combination. Results showed that the characteristic parameters of the RSCf are greatly influenced by R, σ and slope. At low slopes and high ratios of $\sigma/2R$, the characteristic parameters of the RSCf appear linked to a single component of the surface roughness (R or σ). On the contrary, both R and σ are needed to predict the RSCf at high slopes and low ratios of $\sigma/2R$. A simple conceptualization of surface depressions as rectangles, whose shape was determined by R and σ, allowed deriving simple mathematical expressions to estimate the characteristic parameters of the RSCf in function of R, σ and slope. In the case of DS_{max}, the proposed equation performed better than previous empirical expressions found in the literature which do not account for the horizontal component of the surface roughness. The proposed expressions allow estimating the characteristic points of the RSCf with reasonable accuracy and could therefore prove useful for integrating plot-scale overland flow connectivity into hydrological models whenever the RSCf presents a well-defined connectivity threshold.

1. Introduction

Surface micro-topography strongly affects the spatio-temporal distribution of overland flow at the plot scale (Helming et al., 1998; Darboux and Huang, 2005; Antoine et al., 2009; Frei et al., 2010; Appels et al., 2011; Chu et al., 2013; Yang and Chu, 2013). Overland flow is a spatially distributed process whereby depressions progressively overflow and connect to either nearby depressions or to the outflow boundary (Onstad, 1984; Darboux et al., 2002b; Antoine et al., 2011; Chu et al., 2013). During a rainfall event this process starts when the infiltration capacity becomes lower than the rainfall intensity. On rough micro-topographies and ignoring surface detention (i.e., live water) (Fig. 1a), the excess rainfall is at first mostly stored in depressions. In this first stage, depressions do not overflow and thus are not yet connected. However, some outflow may occur due to border effects. This initial and limited flow is generated from the depressions directly connected to the system's outlet and from nearby upstream depressions connected to these initially connected depressions (Peñuela et al., 2013). In a second stage, additional upstream micro-depressions get filled, and start to overflow and connect either to nearby depressions or to the outlet. This results in a gradual and non-linear filling, spilling and connection process. This stage is characterized by a particular phenomenon which consists

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Nomenclature

$z(x)$	elevation of the point x (mm)
l	lag distance between two points (mm)
$\gamma(l)$	variogram (mm^2)
σ	sill of the variogram expressed as the standard deviation (mm)
R	range of the variogram (mm)
C	ratio of surface connected to the outlet to the total surface of the plot (m^2/m^2)
C_0	ratio of surface initially connected to the outlet to the total surface of the plot (m^2/m^2)
C_{CT}	ratio of surface connected to the outlet at the connectivity threshold to the total surface of the plot (m^2/m^2)
DS	depression storage (mm)
DS_{max}	maximum depression storage (mm)
DS_{CT}	depression storage at the connectivity threshold (mm)
RDS = DS/DS_{max}	relative depression storage (mm/mm)
RDS_{CT}	relative depression storage at the connectivity threshold (mm/mm)
A	area occupied by stored water (mm^2)
n	number of depressions
L	length of the longitudinal profile (mm)
α	slope angle of the profile (rad)
β	angle given by arctan($\sigma/2R$) (rad)

of a threshold relationship between rainfall excess and overland flow (Fig. 1a). When the excess cumulative rainfall volume exceeds a certain threshold value, a sharp increase in the generated overland flow is observed as a consequence of the rapid establishment of hydraulic connections between different parts of the system. This threshold phenomenon, which is consistent with percolation theory (Berkowitz and Ewing, 1998) and characteristic of random media (Berkowitz and Ewing, 1998), has been observed in overland flow at the plot scale (Darboux et al., 2002a; Frei et al., 2010; Peñuela et al., 2013; Yang and Chu, 2013). Around this threshold, the overland flow process evolves from a predominant filling process to a predominant spilling process. This second stage finishes when all the micro-depressions are completely filled. The whole soil surface is then connected to the outlet and overland flow consists exclusively in a spilling process. Neglecting surface detention dynamics, steady state overland flow is reached at this point (Fig. 1a).

The spatio-temporal distribution of the overland flow process is affected by structural features of the soil micro-topography. For instance, when increasing surface roughness and thus the maximum amount of water that can be stored in surface depressions, the runoff threshold is delayed (Darboux and Huang, 2005; Chu et al., 2013) and total runoff is decreased (Kamphorst et al., 2000; Chu et al., 2013). Surface slope gradient is another important terrain attribute that may interact with surface roughness to affect functional hydrological connectivity. On rough surfaces particularly, slope gradient can dramatically affect the depression storage (Onstad, 1984; Kamphorst et al., 2000), runoff and the development of preferential flow paths (Bracken and Croke, 2007). Changing the slope gradient modifies the balance between water fill and water spill processes and therefore also changes the dynamics and spatial distribution of overland flow. Low slopes favor the filling of depressions. Overland flow is therefore less likely to occur and the occurrence of the above mentioned threshold in runoff is delayed (Yang and Chu, 2013). As slope increases, the volume of water stored in depressions decreases and a higher number of parallel flow paths connecting upslope areas to downslope areas can be identified. This results in a higher drainage efficiency, i.e., a spill-dominated regime and an earlier occurrence of the runoff threshold (Yang and Chu, 2013).

In order to represent the full complexity of overland flow processes and the effects produced by surface roughness and slope, it would be necessary to provide spatially-distributed hydrological models with subgrid micro-topographical information. However, the use of a high resolution DEM with cm to mm resolution would strongly increase computational and data requirements of hydrological simulations. Equally problematic would be the acquisition of such data over large areas. Because of these high requirements, existing hill-slope or watershed-scale distributed hydrological models do not physically model the process of overland flow generation at the subgrid scale. Models generally simplify the hydrological representation of the micro-topography using two effective parameters, the maximum depression storage (i.e., maximum volume of water that the soil is able to store in surface depressions; DS_{max}) and the friction factor (i.e., resistance to flow) (Singh and Frevert, 2002; Smith et al., 2007). These

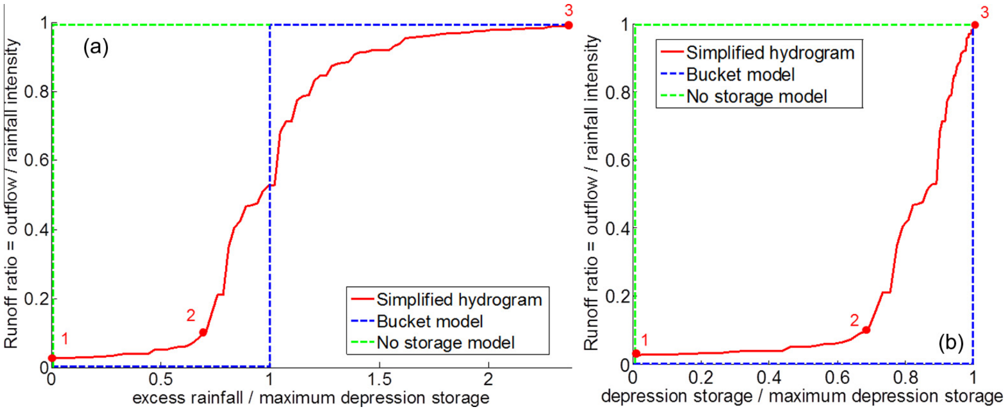

Fig. 1. Comparisons of different simplified representations of overland flow generation as a function of (a) excess rainfall normalized by maximum depression storage and (b) depression storage normalized by maximum depression storage. The no storage model assumes zero depression storage. The bucket model assumes that runoff occurs only after all depressions have been filled. The simplified hydrograph is based on the gradual filling of depression and spilling of water as determined through a conditional walker technique applied to a 3-D representation of surface micro-topography (Antoine et al., 2009). (1 = runoff from areas initially connected to the outlet; 2 = runoff threshold; 3 = steady state).