Effects of Surface Microtopography on Hydrologic Connectivity

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Abstract

Land surface is generally not smooth. The existence of puddles breaks the continuity of various hydrologic features/properties. The spatial connectivity of topographic surfaces has significant influence on a series of hydrologic and geomorphologic processes and results in localized and independent hydrologic mass balance. This study centers on examining the effects of surface microtopography on hydrologic connectivity. An instantaneous-profile laser scanner is utilized to acquire high-resolution DEMs of surfaces with varying microtopographic characteristics. A puddle delineation software package is used to delineate the surfaces and quantify the relationships of puddles. Particularly, both structural and functional hydrologic connectivity properties are examined. In addition, the effects of DEM resolutions on hydrologic connectivity are investigated. It is found that the approach of spatial mapping of the connected areas is capable of describing the spatial complexity of connectivity of topographic surfaces. The surfaces of different microtopographic features have unique changing patterns of normalized discharge, which provides promising information to better understand the related hydrologic processes.

Introduction

Surface microtopography has been identified as one of the major factors that affect the hydrologic processes and the related mass balance (Moore and Larson 1979; Ullah and Dickinson 1979; Ahuja et al. 1982; Onstad 1984; Evett and Dutt 1985; Sneddon and Chapman 1989; Barros et al. 1999; Planchon and Darboux 2001; Darboux et al. 2002; Hayashi et al. 2003; Darboux and Huang, 2005; Thompson et al. 2010). Its influences on the hydrologic processes are due to the local irregularities of land surface, such as the existence of depressions, rills, and ridges. These topographic features show the spatial variability and heterogeneity, and play a dominant role in collecting and storing rainwater, controlling overland flow generation, and modifying runoff patterns (Ullah and Dickinson 1979; Zhang and Cundy 1989; Huang and Bradford 1990; Dunne et al. 1991; Darboux et al. 2002; Darboux and Huang 2005; Thompson et al. 2010). However, research is still needed to examine, in detail, how surface microtopography affects these hydrologic processes.

The concept of hydrologic connectivity has been proposed and used in many areas in recent years to address the related hydrologic and environmental issues (Brierley et al. 2006; Bracken and Croke 2007; Antoine et al. 2009). The examples include...
determination of preferred flow paths in aquifers with higher conductivity values and quantification of connectivity patterns of soil moisture in dry and wet seasons (Western et al. 2001). The connectivity properties that exhibit in many fields have an important influence on hydrologic behavior. In surface water hydrology, connectivity has been referred to as the continuous passages or links between landscape features to transfer water and the related mass over land surfaces (Pringle et al. 2003; Bracken and Croke 2007; Tetzlaff et al. 2007). Examining the hydrologic connectivity properties of land surfaces enables one to improve the understanding of the related hydrologic processes (Darboux et al. 2002; Antoine et al. 2009; Appels et al. 2011).

Different hydrologic connectivity indicators have been proposed to characterize the connectivity properties of land surfaces and describe the responses of a hydrologic system to varying microtopographic conditions. The indicators can be categorized into two types: structural hydrologic connectivity (SHC) and functional hydrologic connectivity (FHC). SHC represents the hydrologic connectivity properties of static topographic surfaces (Antoine et al. 2009), while FHC quantifies the hydrologic responses of topographic surfaces to the system inputs. Various models have been developed to characterize FHC (Darboux et al. 2002; Antoine et al. 2009; Appels et al. 2011; Yang and Chu 2012).

This study aims at investigating the effects of surface microtopography on hydrologic connectivity (both SHC and FHC). In addition, the effects of the DEM resolution on hydrologic connectivity are examined. Further efforts are made to improve the understanding of hydrologic processes by using the information from surface delineation and hydrologic connectivity analysis.

Materials and Methods

Three laboratory-scale surfaces (S1-S3) were created to evaluate the effects of surface microtopography on hydrologic connectivity (Figure 1). Surfaces S1 and S2 (Figures 1a - 1b) were mold surfaces with areas of 1,283 cm² and 3,731 cm², respectively, while Surface S3 (Figure 1c) was characterized with randomly distributed soil aggregates with an area of 1,197 cm². The three surfaces were scanned by using an instantaneous-profile laser scanner (Darboux and Huang 2003; Chu et al. 2010) to acquire high-resolution DEMs. The horizontal and vertical resolutions of the scanned DEMs were 0.98 mm and 0.50 mm, respectively. The scanned data for Surfaces S1-S3 were processed to generate 0.4, 0.4, and 0.1 cm DEMs by using the Kriging method. Surface S2 was further interpolated to generate DEMs with coarser resolutions of 0.8, 1.2, and 2.0 cm.

In this study, an improved puddle delineation (PD) software package (Chu et al. 2010) was used to characterize depressions/puddles. The software delineates puddles, their centers, and thresholds at different levels, and effectively characterizes the spatial complexity of topographic surfaces. In addition, the PD software is capable of determining the hierarchical relationships of puddles and dealing with special
topographic conditions, such as flats. Figure 2 shows the user-friendly Windows interface of the PD software.

A puddle-to-puddle (P2P) conceptual model (Yang and Chu 2012) was used to quantify the connectivity properties of land surfaces. The P2P model takes advantage
of the surface delineation results from the PD software and simulates the spatially and
temporally varied hydrologic processes associated with depressions and their
dynamic interactions by characterizing the puddle filling, spilling, merging, and
separating processes. SHC of topographic surfaces was analyzed by characterizing
and quantifying the connected areas of the selected surfaces. In addition, FHC was
investigated by examining the formation/evolution of the connected areas during the
rainfall-runoff processes and the responses of the system to various microtopographic
conditions, i.e., simplified hydrographs. A number of simulations were conducted for
Surfaces S1 – S3. To simplify the discussion, it was assumed that the rainfall was
steady and uniformly distributed and all surfaces were impervious.

Results and Discussion

Surface Delineation Results

Figure 3 shows the spatial distributions of puddles delineated by the PD software for
Surfaces S1 – S3. Distinct spatial distribution patterns of puddles can be observed for
the three surfaces. Surface S1 is dominated by few larger puddles while S2 and S3 are
characterized by a number of smaller puddles of arbitrary shapes. Surface S1 has 4
puddle levels and 10 puddles at the highest level. Surfaces S2 and S3, featuring 11
and 19 puddle levels, respectively, have 38 and 378 puddles at the highest level.

Each of the highest level puddles can be an individual puddle or a combined puddle
that consists of a series of lower-level embedded puddles. In a rainfall-runoff event, a
fully-filled puddle may spill water to downstream or merge with an adjacent puddle
that shares a common threshold to form a higher level puddle. The more puddles and
puddle levels a surface has, the more complex the surface is.
Hydrologic Connectivity Analysis

No ideal smooth surface exists in the natural landscape. Topographic surfaces are often characterized with puddles of varying sizes. These puddles break the connectivity of the surfaces and cause the spatial variability and independent isolated hydrologic mass balance. Figure 4 shows the spatial mapping of connected areas and puddles at the first and highest levels for Surface S1. Each of the connected areas includes a puddle, a threshold, and a number of contributing cells (Fig. 4). During a rainfall event, a puddle may be fully filled and spill water to downstream or another puddle through its threshold, which makes two separate connected areas merge. Gradually, more and more puddles are fully-filled and a larger connected area is formed. If the connected area links to an outlet, an increase in discharge is expected as the connected area expends.

Figure 4. Spatial mapping of puddles and connected areas for Surface S1

Figure 5 shows the spatial distributions of connected areas for Surfaces S2 and S3. Each of the connected areas includes a puddle at the first level. Significant differences in SHC, determined by the irregularity and complexity of the surfaces (e.g., numbers, sizes, and patterns of puddles), can be observed for the two surfaces. For Surface S2, the number of the connected areas is small because of a relative small number of puddles. However, Surfaces S3 is characterized with a great number of small puddles and 19 puddle levels, which result in smaller connected areas.

The uniformity of the distributions of connected areas is related to the surface characteristics and puddle distributions. The DEM with a higher resolution shows more topographic details, such as small puddles, which result in small connected areas. In contrast, a DEM with a larger grid size may smooth out many small puddles and the corresponding surface displays fewer larger connected areas. It hence can be concluded that the approach of spatial mapping of connected areas is capable of describing the spatial connectivity of topographic surfaces and linking to the relevant hydrologic processes.
The formation/evolution of connected areas of a topographic surface during a rainfall-runoff event is a dynamic process determined by the surface characteristics and system inputs, such as spatial and temporal rainfall distributions. Figure 6 shows the relationships of the number of connected areas (NCA) and the ratio of average connected area to entire surface area (rACA-A) with cumulative rainfall normalized by maximum depression storage (rCP-MDS) of the simulations for the three surfaces. The purpose of normalization of cumulative rainfall by maximum depression storage (rCP-MDS), instead of using time or cumulative rainfall as an independent variable is to remove the surface storage effect and make the surfaces of different sizes comparable. NCA follows a decreasing pattern while rACA-A shows an increasing pattern for the simulations for all the three surfaces (Figure 6). However, with an increase in rCP-MDS, the three surfaces show different changing patterns of NCA and rACA-A, especially at the beginning stage of the rainfall-runoff process. Initially, Surfaces S2 and S3 have more connected areas than Surface S1. The NCA of Surface S3 decreases much faster than Surfaces S1 and S2 at the beginning stage (Figure 6), which is due to the frequently occurred P2P processes. The NCA gradually levels off afterwards for the three surfaces (Figure 6). The rACA-A increases with an increase in rCP-MDS for the three surfaces. A surface with a smaller number of puddles (e.g., S1) has higher rACA-A values and shows a more significant increase during the rainfall-runoff process.

Based on the above analysis, it can be concluded that surfaces with various characteristics may have distinct changing patterns of the relationships of NCA and rACA-A with rCP-MDS, which reflect the dissimilarity in the formation/evolution of

Figure 5. Spatial distributions of connected areas (AC) for Surfaces S2 and S3
connected areas. In addition, the P2P dynamics and the formation/evolution of connected areas are particularly crucial at the beginning of the rainfall-runoff process.

Figure 7 shows the simplified hydrographs of the simulations for Surfaces S1 – S3, which represent the relationships of normalized discharge by rainfall input ($r_{Q-P}$) with $r_{CP-MDS}$. Stepwise increases in the simplified hydrographs can be observed for all three surfaces (Figure 7), which can be attributed to the fully-filled puddles and the subsequent increases in connected areas that are linked to the outlet(s). The shapes of the hydrographs depend on the geometric properties and organizations of the puddles, and flow drainage patterns. Surfaces S2 and S3 have smoother hydrographs than Surface S1, which shows “abrupt” stepwise increases (Figure 7). Gradually, $r_{Q-P}$ reaches 1.0 for all three surfaces, which means that the P2P dynamic process is completed and the entire surface is connected to the outlet and makes contributions of runoff water.

Figure 8 shows the simplified hydrographs for Surface S2 with grid sizes of 0.4, 0.8, 1.2, and 2.0 cm. It can be observed that the simulated simplified hydrographs have similar changing patterns for the surface with different resolutions. The simplified hydrographs for finer grid sizes (e.g., 0.4 and 0.8 cm) are close to each other. It takes longer time or more water for the system to reach a steady state for surfaces with a coarser resolution. The differences in the simplified hydrographs for surfaces with various grid sizes can be attributed to: (1) changes in MDS for surfaces with various grid sizes, (2) changes in the distributions and relationships of puddles, and (3) changes in the flow drainage system.
Conclusions

In this study, three small scale surfaces with various microtopographic characteristics were created. The puddle delineation software was utilized for surface delineation and the P2P conceptual model was used to examine the effects of surface microtopography on hydrologic connectivity properties. Conclusions can be summarized as follows:

Connected areas are basic units of topographic surfaces for hydrologic analysis (e.g. overland flow generation). The approach of spatial mapping of the connected areas enables one to describe the spatial complexity of connectivity of land surfaces and link to the relevant hydrologic processes.

Simplified hydrographs are featured by a number of stepwise increases, determined by surface microtopographic characteristics. The simplified hydrographs provide promising information on the influences of surface microtopography on hydrologic processes. Such information helps to understand the potential of overland flow generation, describe the rainfall-runoff process, and quantitatively determine the amount of water needed for the flow system to reach a steady state.

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References


