Advances in Water Resources 78 (2015) 80–93

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

A new modeling approach for simulating microtopography-dominated, discontinuous overland flow on infiltrating surfaces

Jun Yang, Xuefeng Chu *

Department of Civil and Environmental Engineering, North Dakota State University, PO Box 6050, Fargo, ND 58108, United States

ARTICLE INFO

Article history:
Received 13 May 2014
Received in revised form 30 January 2015
Accepted 5 February 2015
Available online 14 February 2015

Keywords:
Overland flow
Microtopography
Puddle dynamics
Depression
Infiltration
Digital elevation model

ABSTRACT

Realistic modeling of discontinuous overland flow on irregular topographic surfaces has been proven to be a challenge. This study is aimed to develop a new modeling framework to simulate the discontinuous puddle-to-puddle (P2P) overland flow dynamics for infiltrating surfaces with various microtopographic characteristics. In the P2P model, puddles were integrated in a well-delineated, cascaded drainage system to facilitate explicit simulation of their dynamic behaviors and interactions. Overland flow and infiltration were respectively simulated by using the diffusion wave model and a modified Green–Ampt model for the DEM-derived flow drainage network that consisted of a series of puddle-based units (PBUs). The P2P model was tested by using a series of data from laboratory overland flow experiments for various microtopography, soil, and rainfall conditions. The modeling results indicated that the hierarchical relationships and microtopographic properties of puddles significantly affected their connectivity, filling–spilling dynamics, and the associated threshold flow. Surface microtopography and rainfall characteristics also exhibited strong influences on the spatio-temporal distributions of infiltration rates, runoff fluxes, and unsaturated flow. The model tests demonstrated its applicability in simulating microtopography-dominated overland flow on infiltrating surfaces.

1. Introduction

The importance of surface microtopography in surface runoff, infiltration, and other hydrologic processes has been emphasized [17,25,26,24,16,13,42,12,7]. The spatial variability of surface microtopography influences overland flow generation [32], delays the initiation of surface runoff [16], and enhances the retention of runoff water [1]. It has been found that surface microtopography controls spatial and temporal variations of overland flow depth and velocity [47,27,18,19]. In addition, greater depths of water ponded in microtopographic depressions tend to increase infiltration [18,37] and unsaturated flow [30]. The spatial variability in surface microtopography also affects surface–subsurface exchange and runoff generation for riparian wetlands [20].

A series of modeling studies have demonstrated the importance of quantifying the actual surface topography and the related hydraulic effects in hydrologic models [47,41,18]. Due to the existence of depressions on topographic surfaces, overland flow often features with discontinuous characteristic and threshold-controlled puddle filling and spilling behaviors [12]. Such a topography-dominated, threshold-driven overland flow process varies spatially and temporally and is referred to as puddle-to-puddle (P2P) dynamics [12]. While the impacts of surface topography on runoff and infiltration processes have been well understood, limited effort has been made to quantitatively characterize such impacts [26,24,16].

In the recent decade, research efforts have been made to conceptually model the hydrologic role of surface microtopography and quantify hydrologic connectivity and the associated dynamic variability in contributing areas. Darboux et al. [15] developed a conditional-walker method to simulate depression filling and water redistribution on rough surfaces, and further evaluate the influence of surface microtopography on discharge. Antoine et al. [4] applied a model similar to the one developed by Darboux et al. [15] and further proposed a functional connectivity indicator (relative surface connection function) that linked surface connection to the filling of surface depression storage. Shaw et al. [38] developed a conceptual model to simulate the fill-spill of depressions and applied it to quantify runoff contributing areas of the wetlands in the Prairie Pothole Region with assumptions of impervious surfaces and uniformly-distributed water input.

The aforementioned conceptual models did not take into account the spatio-temporally varying rainfall and infiltration processes. Instead, a steady and uniform rainfall distribution was assumed. In addition, instantaneous water transfer over a

---

* Corresponding author. Tel.: +1 701 231 9758; fax: +1 701 231 6185.
E-mail address: xuefeng.chu@ndsu.edu (X. Chu).

http://dx.doi.org/10.1016/j.advwatres.2015.02.004
0309-1708/

topographic surface was commonly assumed in such conceptual models (e.g., [15,14,4,5,38], which may not be valid for a larger scale hydrologic system. To consider the runoff water transferring time and depression storage, Antoine et al. [3] integrated the connectivity information of subgrids (relative surface connectivity function) into the hydrograph by implementing two corrective procedures (weighted-source and weighted-surface). A uniform slope and 1D sheet flow were assumed in their modeling.

Various physically-based distributed models have been widely used to simulate overland flow processes. In such models, the Saint–Venant equations or the simplified forms (diffusion wave and kinematic wave equations) are numerically solved. However, these models are often limited to the modeling of continuous overland flow. Particularly, they may suffer from stability and convergence problems due to the highly non-linear nature of the governing equations and abrupt slopes caused by topographic variations [44,39,23,41]. To avoid the numerical oscillations, many hydrologic models rely on smoothing the digital elevation models (DEMs) by removing depressions [41,29,40]. In addition, such numerical models are computationally intensive and time consuming. For instance, Antoine et al. [3] found that the computation time of a numerical diffusion wave model for a small plot (1×1 m^2 and 2-mm DEM resolution) was three orders of magnitude slower (100 days) than that of their simplified conceptual model (10 min). Importantly, those numerical models may not be able to account for the important hydrologic roles of surface depressions and realistically simulate the P2P dynamics and the resulting discontinuous overland flow (e.g., [18,19,40]). Chu et al. [12] developed a conceptual P2P modeling framework, which focused on characterization of surface microtopography and modeling of the dynamic P2P filling, spilling, merging, and splitting processes by assuming instantaneous water transfer. The conceptual model was also applied to quantify the spatio-temporal variability in hydrologic connectivity [46].

This study focuses on improving the process-based overland flow modeling techniques. It is aimed to develop a new hydrotopographic modeling framework to characterize the dynamic P2P filling–spilling–merging–splitting overland flow processes and the associated threshold behaviors under the influence of surface microtopography. The specific objective is to develop a quasi-3D physically-based model that couples a hierarchical overland flow model with a subsurface model. The former is a diffusion wave model for simulating areal surface runoff, while the latter is a modified Green–Ampt model [9] for simulating point (cell based) infiltration and unsaturated flow to account for the infiltration-excess overland flow (Hortonian overland flow) mechanism. Furthermore, testing of the P2P model is performed by using real observed data from overland flow experiments for various microtopography, soil, and rainfall conditions. This study builds on the conceptual P2P modeling framework [12]. However, the P2P model presented herein simulates the physical overland flow processes, and accounts for infiltration and unsaturated flow. To the best of our knowledge, this is the first attempt to simulate microtopography-dominated, discontinuous overland flow over infiltrating surfaces in conjunction with the modeling of threshold-controlled, P2P dynamics under varying microtopography, soil, and rainfall conditions.

2. Development of the P2P overland flow model

2.1. Overview of the P2P overland flow modeling framework

The P2P modeling framework includes both cell-to-cell (C2C) and P2P flow routing for a set of puddle-based units (PBUs) in a well-delineated, cascaded drainage system [12]. The flowchart of the P2P overland flow model developed in this study is shown in Fig. 1. The model input data include basic simulation parameters, surface DEM, soil hydraulic property parameters, meteorologic data, and puddle delineation results from the PD program [13] (Fig. 1). In the P2P model, a series of nested loops are implemented for water routing, including time loop, basin loop, PBU loop, C2C loop, and P2P loop (Fig. 1). A topographic surface may consist of a number of basins, depending on the surface microtopographic characteristics and the number of outlets at the boundaries of the surface. Within a time step, water routing is performed for all basins (Fig. 1). Overland flow in a basin is essentially controlled by a cascaded P2P drainage system (Fig. 2). This system consists of a series of PBUs determined by surface depressions, which break the continuity and connectivity of the topographic surface (Fig. 2). The PBUs have unique hydrotopographic characteristics and exhibit strong spatial and temporal variability (Fig. 2).

Based on the puddle delineation results from the PD program [13], the P2P model tracks the PBUs of each basin and detects their upstream–downstream relationships. PBU is a basic simulation unit within the basin routing loop (Fig. 1). A PBU consists of a number of contributing cells (DEM grids) and a highest-level puddle, which may include a group of lower-level embedded puddles [12] (Fig. 2). The threshold of the highest-level puddle connects this PBU to its downstream PBU (Fig. 2). Overland flow is routed for all PBUs by following their sequences in the well-delineated, cascaded P2P flow drainage system [12] (Fig. 1). Two routing procedures (i.e., C2C and P2P) are implemented for all PBUs (Figs. 1 and 2) [12]. The C2C water routing transfers water from upstream to downstream cells, eventually to the water-ponded cells (i.e., puddle cells), while the P2P water routing simulates the dynamic filling and depleting of puddles and their interactions (i.e., spilling, merging, and splitting) (Fig. 2). The simulation for a basin ends when flow routing is completed for all PBUs in the basin, and the modeling continues until all basins are simulated (Fig. 1).

In the P2P model, the water sources of any overland cell include lateral inflow from its upstream cell(s) and rainfall input while the sink terms consist of lateral outflow to its downstream cell, infiltration, and evaporation (Fig. 2). The modified Green–Ampt model [9] is used to simulate infiltration-excess overland flow. Non-uniform and unsteady rainfall and evaporation are considered in the P2P model by specifying a number of rainfall and evaporation zones. The evaporation of ponded water in puddles is estimated based on Allen et al. [2].

2.2. C2C overland flow routing

The PBUs on a topographic surface may have varying sizes and irregular geometric shapes. To facilitate the flow routing on such irregular spatial domains, a DEM-based drainage network is identified for each PBU based on the D8 method [36] (Fig. 3). The drainage network of a PBU is determined by tracking all contributing cells using their flow directions backward from the puddle center or outlet of the PBU. The sequence of the cells in the derived flow drainage network essentially records the contributing relationships from one cell to another cell, or from multiple cells to one cell (Fig. 3). By taking advantage of these contributing relationships of cells in the flow drainage network, the C2C overland flow routing is conducted by simulating water movement from the most upstream cells to water-covered cells in the puddle(s) of the PBU (Fig. 3). Note that the water-ponded puddle cells are excluded in the C2C routing, and that the C2C simulation domain may change with the rising/falling in the ponded water levels of the puddles as more/fewer cells are covered by water (Fig. 3). The P2P routing for a PBU initiates after the C2C routing is completed (Fig. 1).