Water Science and Engineering 2016, 9(3): 249–255

HOSTED BY ELSEVIER

Available online at www.sciencedirect.com

Water Science and Engineering

journal homepage: http://www.waterjournal.cn

Distributed hydrological models for addressing effects of spatial variability of roughness on overland flow

Sheng-tang Zhang [a,*], Yin Liu [b], Miao-miao Li [a], Bo Liang [a]

[a] College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China
[b] College of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Received 10 May 2015; accepted 2 December 2015
Available online 9 July 2016

Abstract

In this study, we investigated the origin of the overland flow roughness problem and divided the current overland flow roughness research into three types, as follows: the first type of research takes into account the effects of roughness on the volume and velocity of surface runoff, flood peaks, and the scouring capability of flows, but has not addressed the spatial variability of roughness in detail; the second type of research considers that surface roughness varies spatially with different land usage types, land-cover conditions, and different tillage forms, but lacks a quantitative study of the spatial variability; and the third type of research simply deals with the spatial variability of roughness in each grid cell or land type. We present three shortcomings of the current overland flow roughness research, including (1) the neglect of roughness in distributed hydrological models when simulating the overland flow direction and distribution, (2) the lack of consideration of spatial variability of roughness in hydrological models, and (3) the failure to distinguish the roughness formulas in different overland flow regimes. To solve these problems, distributed hydrological model research should focus on four aspects in regard to overland flow: velocity field observations, flow regime mechanisms, a basic roughness theory, and scale problems.

Keywords: Distributed hydrological model; Overland flow; Roughness; Spatial variability

1. Introduction

Overland flow, also known as sheet flow or overflow, is gravity-driven flow that occurs on channelized surfaces. It is formed when rainfall or snowmelt does not infiltrate the soil or collect in surface depressions (i.e., channels or surface water bodies). Overland flow generally occurs near watershed divides on the upper part of a slope, and is considered to be shallow water flow that covers the slope. It forms sheet-like flows when there is a large flow rate, but can become a brooklet intertwined through separate mesh trickles. It is easily affected by changes in resistance and micro-terrain, and also has non-unique flow directions.

Overland flow forms the major part of rivers, streams, lakes, etc., and its movement towards water bodies is accompanied by pollutant transport and soil leaching. Therefore, studying overland flow is important to understanding slope hydrologic processes and soil erosion mechanisms. Theoretically, distributed hydrological models can accurately simulate the overland flow process using precise discrete grid cells (Wang and Hjelmfelt, 1998). However, in reality, compared to lumped hydrological models, distributed models sometimes produce unsatisfactory or even incorrect simulations of the velocity fields among the grid cells, even though they can simulate the runoff at the watershed exit by various means (e.g., parameter adjustment) (Mügler et al., 2011; McDonnell and Beven, 2014). The main cause of the

This work was supported by the National Natural Science Foundation of China (Grants No. 41471025 and 40971021) and the Natural Science Foundation of Shandong Province (Grant No. ZR2014DM004).
* Corresponding author.
E-mail address: zst0077@163.com (Sheng-tang Zhang).
Peer review under responsibility of Hohai University.

http://dx.doi.org/10.1016/j.wse.2016.07.001

problem stated above is the simple processing of the complex slope roughness effects in distributed hydrological models. There have been numerous achievements in the study of roughness. However, previous research has differed in levels and has arrived at different conclusions because roughness varies not only with boundary characteristics but also with flow velocity, water depth, and other hydraulic factors. Even a tiny change in roughness can have a marked impact on the flow characteristics (Darboux et al., 2002; Candela et al., 2006; Sahoo et al., 2006). Actual conditions of basins are varied. When water channel networks develop in humid areas, overland flow will soon reach a river system, and slope characteristic factors have little effect in these areas. In contrast, in arid areas, overland flow has a longer pathway to the river system, and the main mechanism of flow generation is excess infiltration. When water flow is impeded by surface roughness, it will affect the final runoff volume because the infiltration rate is high and the infiltration will continue along the pathway. In this sense, different climatic regions have different surface roughness effects on overland flow. Different hydrological models can be applied to different climatic regions due to the diverse flow generation patterns (Liu et al., 2009). The numerous factors and their interactions with roughness further complicate the effect.

In this study, we investigated the origin of the overland flow roughness problem, classified the methods used to address it, and pointed out the inappropriate aspects of surface roughness research in theory. Moreover, we present possible solutions to the roughness problem based on the current research status.

2. Origin of roughness problem

Surface roughness was first investigated by de Chezy, who presented a formula of resistance including the Chezy coefficient. Later, Ganguillet and Kutter introduced the concept of roughness when they studied the Chezy coefficient. Subsequently, Manning established the Manning resistance formula, which was translated later to another formula with the roughness coefficient, and this coefficient is the so-called roughness at present (Smith et al., 2007). Through these studies, roughness has developed a definite meaning: a comprehensive coefficient that represents the blocking effect of the solid coarse surface on flow. In regard to open channel flow, roughness is an integrated hydraulic resistance coefficient. It varies not only with the surface characteristics but also with the flow volume, water depth, and other hydraulic factors. In the investigation of open channel flow, an increasing number of researchers have begun to consider the roughness change in different flow regimes. The interactions between flow quantity, water depth, and velocity in different regimes make roughness a complicated problem. Wu and Christensen (2007) used a wind tunnel test to study the effects of surface roughness on velocity distribution, shear stress, and other hydraulic factors of turbulence.

Unlike open channel flow, overland flow is usually shallow flow on a slope, which can be solved with the Saint-Venant equation and the Manning formula as follows:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial q}{\partial l} = r \\ v = \dfrac{s_{\mathrm{f}}^{1/2} h^{2/3}}{n} \end{cases} \tag{1}$$

where h represents the average depth of overland flow, t is time, q represents the flux per unit width, r is the net input flux, l is the slope length, s_{f} represents the friction gradient that approximately equals the directional gradient, v is the overland flow velocity, and n is the Manning roughness coefficient of the slope.

Currently, researchers use the available knowledge of pipe and open channel flow to address the overland flow roughness coefficient in Eq. (1). However, because the overland flow is formed by precipitation and moves along the slope, it has various flow directions, as opposed to open channel flow.

Overland flow changes speed and flow direction frequently because of the effects of water depth, micro-terrain, resistance, and other factors. The pathway of overland flow may differ because of rainfall volume, humidity, or other climatic conditions. A distributed hydrological model used to simulate overland flow is generally affected by the overland flow characteristics, which change easily according to earth surface, hydrological, and meteorological conditions.

In general, shallow flow is significantly affected by the friction of the solid surface, and is simultaneously affected by the surface geological types, land usage types, cultivation, and other spatial variation factors. Consequently, slope roughness has spatial variability, which complicates the overland flow roughness problem. Because of the unique features stated above, overland flow roughness has received considerable attention. Overland flow is easily affected by the change of resistance and micro-terrain because of thin-layer flow. Therefore, flow direction and distribution become complex. Macroscopic slope topography determines the large-scale direction of convergence, but at the grid scale, the variations of the micro-terrain and resistance in different directions within the inner grid will affect the pathway of overland flow in the grid cell. Inaccurate simulations of these effects will result in a loss of information about the real flow path and may lead to biases of flow length (Liu et al., 2012). Thus, the simulation results of distributed hydrological models will be highly variable.

3. Current research on overland flow roughness

Overland flow roughness has become the most active research area in hydrology, and substantial efforts have been made by researchers with different research objectives. After analyzing their achievements, we divided all of the methods for handling roughness into three types.

3.1. First type

In the first type of methods, it is assumed that roughness affects the volume and velocity of surface runoff, flood peaks, and the scouring capability of flow (Lumbroso and Gaume,