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Combining dual-continuum approach with diffusion wave model to include a preferential flow component in hillslope scale modeling of shallow subsurface runoff

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ABSTRACT

In the absence of overland flow, shallow subsurface runoff is one of the most important mechanisms determining hydrological responses of headwater catchments to rainstorms. Subsurface runoff can be triggered by preferential flow of infiltrating water frequently occurring in heterogeneous and structured soils as a basically one-dimensional (1D) vertical process. Any attempt to include effects of preferential flow in hydrological hillslope studies is limited by the fact that the thickness of the permeable soil is mostly small compared to the length of the hillslope. The objective of this study is to describe preferential flow effects on hillslope-scale subsurface runoff by combining a 1D vertical dual-continuum approach with a 1D lateral flow equation. The 1D vertical flow of water in a variably saturated soil is described by a coupled set of Richards' equations and the 1D saturated lateral flow of water on less permeable bedrock by the diffusion wave equation. The numerical solution of the combined model was used to study rainfall-runoff events on the Tomsovska hillslope by comparing simulated runoff with observed trench discharge data. The dual-continuum model generated the observed rapid runoff response, which served as an input for the lateral flow model. The diffusion wave model parameters (i.e., length of the contributing hillslope, effective porosity, and effective hydraulic conductivity) indicate that the hillslope length that contributed to subsurface drainage is relatively short (in the range of 25–50 m). Significant transformation of the 1D vertical inflow signal by lateral flow is expected for longer hillslopes, smaller effective conductivities, and larger effective porosities. The physically-based combined modeling approach allows for a consistent description of both preferential flow in a 1D vertical soil profile and lateral subsurface hillslope flow in the simplest way.

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1. Introduction

Shallow subsurface runoff (also referred to as interflow, stormflow or throughflow) is recognized as one of the most important mechanisms determining hydrological responses of headwater catchments to rainstorms. It usually develops as shallow saturated lateral flow at the sloping interface between a more permeable surface soil layer and the less permeable underlying soil or bedrock strata. Normally, this type of flow occurs only for a short period of time as an immediate response to an intense rainfall event. The onset of shallow subsurface runoff is commonly accelerated by the presence of preferential pathways in a soil profile. Thus, preferential flow is recognized as a significant factor in runoff formation at the hillslope scale [e.g., 1–3].

Transport processes at the hillslope scale are inherently of three-dimensional (3D) nature. Recently, a few applications of 3D modeling based on Richards' equation for water flow and advection-dispersion equation for solute transport were presented [4–6]. Nevertheless, the water dynamics at the hillslope scale are more frequently described using two-dimensional (2D) models [e.g., 7–9]. However, the 2D approaches are still difficult to apply for large spatial configurations (i.e., hundreds of meters long hillslopes) since computationally demanding numerical solution of the governing equations is required. Therefore, subsurface water dynamics in a hillslope segment was proposed to be decoupled to one-dimensional vertical flow and one-dimensional (1D) lateral flow along the soil/bedrock interface [10–12]. Saturated subsurface flow can be, in principle, described by a one-dimensional diffusion wave (Boussinesq-type) equation. However, the approach of coupling the two one-dimensional models represents a substantial simplification of the reality such that it needs additional experimental evidence. The validity of such simplification for describing fast flow

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responses at the hillslope scale involving preferential flow effects remains a challenge.

The kinematic wave approximation of saturated subsurface flow was proposed as a simple model for predicting subsurface flow [e.g., 13,14]. The hillslope-storage Boussinesq equation, based on either kinematic or diffusion wave approach, was theoretically developed for various spatial hillslope configurations by Fan and Bras [15], Troch et al. [16,17] and Paniconi et al. [10] focusing on mathematical description of shallow subsurface flow generation. Subsequently, Hilberts et al. [18] introduced a fully coupled model (of 1D vertical Richards' equation and lateral Boussinesq equation) and found a good match with results obtained with a 3D model based on the Richards' equation. However, comparisons of model predictions with experimental data were not presented in these studies, and preferential flow effects were neglected in the modeling approach.

Experimental findings of Vogel et al. [19] based on natural concentrations of the stable oxygen isotope in hillslope discharge demonstrated fast soil water dynamics. In their study, the preferential flow and transport was described using vertical one-dimensional dual-continuum model of Gerke and van Genuchten [20]. At their hillslope discharge analysis, Vogel et al. [19] hypothesized that the contributing hillslope was not long enough to cause any significant modifications in the transformation of the inflow signal (i.e., the lateral component of shallow subsurface flow could be neglected); thus the vertical one-dimensional model could be used alone to predict shallow subsurface runoff and oxygen concentrations. A more detailed analysis of the lateral flow effects contributing to measured shallow subsurface runoff was, however, beyond the scope of their study.

The present study focuses on numerical modeling of shallow subsurface runoff at the hillslope scale. The objective was to develop and test a model that includes a preferential flow component in the description of shallow subsurface runoff along hillslopes with structured soils, and test if the proposed model can represent the most relevant hillslope scale processes. The modeling approach combines two forward-coupled 1D approaches: vertical dual-continuum approach and lateral single-continuum diffusion wave model. The research issues were to test: (i) if the modeling approach works in principle, (ii) if it can be successfully applied to simulate the observed shallow subsurface stormflow hydrographs, and (iii) to confirm that the combined approach is able to transform the rapid preferential-flow-dominated signals into measured runoff responses. More specifically, we analyzed how the signal transformation of vertical flow to lateral runoff depends on hillslope length, effective porosity, and effective hydraulic conductivity.

2. Materials and methods

2.1. Experimental site

The experimental hillslope site Tomsovka is located in the small mountain catchment Uhlirska, Jizera Mountains, Czech Republic. Total area of the catchment is 1.78 km^2, average altitude reaches 820 m above sea level, annual precipitation exceeds 1300 mm/year, and annual mean temperature is 4.7 °C. The studied hillslope is covered with grass (*Calamagrostis villosa*) and spruce (*Picea abies*). The average slope at Tomsovka is about 14%.

Hydrological and micrometeorological conditions are monitored with high temporal resolution at Tomsovka [21]. Subsurface hillslope discharge is measured via an 8 m experimental trench of about 80 cm depth. It consists of two individual sections (A and B), each 4 m wide (Fig. 1). Shallow subsurface hillslope discharge is collected separately in each section at the depth of about 75 cm. The discharge rates are measured continuously by tipping bucket

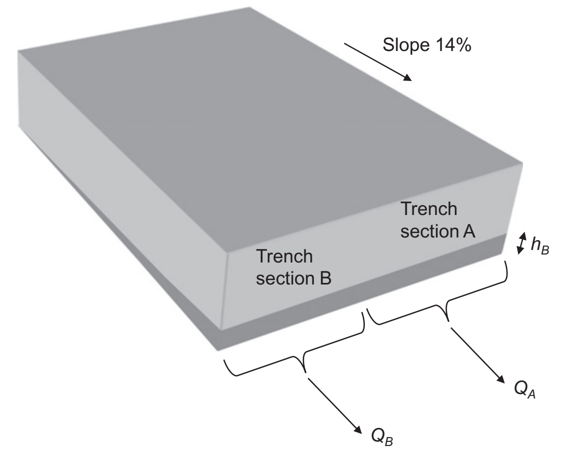

Fig. 1. Schematic of the experimental trench for collecting hillslope discharge at the Tomsovka site. The discharge is collected 75 cm below the soil surface with 4-m long PVC runoff pipes pushed into the soil and measured by tipping buckets separately for the two trench sections (Q_A and Q_B); h_B is the depth of saturated subsurface stream (lateral flow), which occurs episodically in response to major rainstorms.

fluxmeters during the vegetation seasons (from May to October). The hillslope length contributing to measured subsurface discharge was estimated to be about 25 m [22], although the geographic watershed divide is located approximately 130 m above the experimental trench, winding through a gently sloping plateau. The contributing hillslope length estimated by Hrncir et al. [22] resulted from the comparison of trench flow data and discharge observed in the creek gauging station (assuming that the subsurface flow forms a dominant portion of the catchment discharge).

The typical soil profile at Tomsovka is about 70 cm deep; soil is sandy loam classified as Dystric Cambisol. The soil profile consists of three layers with different hydraulic properties. The soil has well-developed internal structure with a broad range of pore sizes. The three soil layers are underlain by a compact transition zone at the depth of about 70 cm, followed by granite bedrock. The soil hydraulic parameters characterizing each layer were derived from laboratory measurements, where undisturbed 100 cm^3 soil samples and 1000 cm^3 soil cores were used to determine soil water retention parameters and saturated hydraulic conductivity, respectively [23]. In addition, saturated hydraulic conductivity of the transition zone was determined using a tension disk infiltrometer.

Significant preferential flow effects, affecting the soil water response to precipitation, were reported for the same site by Sanda and Cislerova [23] and Hrncir et al. [22]. Preferential flow was attributed to highly conductive pathways along decayed tree roots and structural pores as well as by the spatial variability of local soil hydraulic properties. Soil water pressure within the soil profile was monitored using a set of automated tensiometers, installed at five locations at three different depths below the soil surface, between 1 and 20 m distance above the experimental trench. The present study makes use of the data measured at the Tomsovka site over the period from May 2007 to October 2009.

2.2. One-dimensional lateral flow model (LatFlow)

Upon sufficiently intensive rain, infiltrating water percolates vertically downward in the soil profile to the impermeable bedrock (or the top boundary of a low permeable soil layer) where a saturated layer is being gradually formed (Fig. 2). In the saturated layer, water flows laterally in the direction determined by the local gradient of the soil/bedrock interface, which usually does not differ much from the soil surface elevation gradient. The short-term

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