

MODELING SUBSURFACE RUNOFF AT THE HILLSLOPE SCALE USING THREE CONCEPTUALLY DIFFERENT APPROACHES

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Introduction

Efficient quantitative description of the hillslope response to rainstorm remains one of the most important problems of the catchment hydrology. The success in modeling of flow processes at the hillslope scale is related to the adequate choice of theoretical assumptions constituting the conceptual model of the phenomena and to the appropriate selection of methods for the determination of the model parameters.

Subsurface hillslope runoff is studied in detail at the experimental catchment Uhlirská (North Bohemia). Three different modeling approaches are compared.

Material and methods

Experimental site

The study area is located at the Uhlirská catchment (drainage area 1.87 km², average altitude 820 m), situated in Jizera Mountains. The basin is covered with vegetation consisting of young spruce monoculture interspersed with Bentgrass. Typical hillslope soil profile consists of about 10–20 cm of black peaty layer, 0–10 cm of greyish gleyic layer, 30 cm of ocher loamy-sand layer, and 30 cm of eluvial yellowish-brown layer gradually transiting into the weathered granite bedrock. The soil has been classified as Dystric Gleyic Cambisol.

Automated data collection devices are used for continuous monitoring of the subsurface runoff (Sanda and Cislerova, 1998). In the trench, the subsurface outflow is gathered from three soil horizons of two sections (A and B), instrumented with 4 m long stainless steel collector. The instrumented horizons approximately correspond to the soil layer interfaces. The discharge from the individual sections and horizons is measured by tipping-bucket flowmeters. The soil water dynamics is monitored at several locations by means of tensiometers.

Compared approaches, flow equations

In the first approach, one-dimensional variably saturated vertical flow is coupled with one-dimensional saturated subsurface flow along the soil-bedrock interface (Vogel, 2005). The saturated downhill flow is described by a one-dimensional diffusion wave equation while the vertical flow is modeled by means of a dual set of one-dimensional Richards' equations.

The one-dimensional vertical variably saturated flow takes place in a dual continuum system, which consists of two mutually communicating flow domains: the soil matrix domain and the preferential flow domain (Gerke

and van Genuchten, 1993). The flow of water is described by a pair of Richards' equations allowing exchange of water between the pore domains. The exchange of water is directly proportional to the pressure head difference between the matrix and the preferential flow domain.

The shallow subsurface runoff is approximated by a one-dimensional saturated stormflow model, employing a Boussinesq type equation.

In the second approach, zero-dimensional nonlinear morphological element model coupled with a zero-dimensional soil water storage component is used (Bertagnoli *et al.* 2004).

Following expressions for the specific water discharge q_f (LT^{-1}) and deep percolation rate q_{dp} (LT^{-1}) respectively are used

$$q_f(t) = \frac{(1-c_p) Q_0}{A} e^{\frac{s(t)}{m}} \quad (1)$$

$$q_{dp}(t) = \frac{c_p Q_0}{A} e^{\frac{s(t)}{m}} \quad (2)$$

where c_p is the loss coefficient, Q_0 minimum water discharge (L^3T^{-1}), A watershed area (L^2), $s(t)$ is the soil water content (L) and m indicate the water discharge variation rate parameter (L).

The actual soil water content is obtained from the water balance equation

$$s(t) = s(t - \Delta t) + (P(t) - ET(t) - q_f(t) - q_{dp}(t)) \Delta t \quad (3)$$

where P is the precipitation rate (LT^{-1}), and ET stands for the evapotranspiration rate (LT^{-1}).

The third approach is based on the storage discharge relationship adapted from a simplified steady state theory for the saturated subsurface downslope flow (TOPMODEL, Beven (2001)). The version of TOPMODEL used in this study is based on the original assumptions of an exponential relationship between transmissivity and storage deficit. This assumption, together with the quasi-steady state and hydraulic gradient assumptions, leads to a topographic similarity index (Beven and Kirkby, 1979)

$$I_i = \ln \frac{a_i}{T_0 \tan \beta_i} \quad (4)$$

where I_i is the soil topographic index (-), T_0 lateral transmissivity when soil is just saturated (L^2T^{-1}), a_i area of the hillslope that drains through point i (L^2) and β_i local surface topographic slope.

The recession of the hydrograph is computed by relating the baseflow discharge q_b (LT^{-1}) to the average deficit \bar{D} [L]:

$$q_b = q_0 e^{-\frac{\bar{D}}{m}} \quad q_0 = e^{-i} \quad (5)$$

where m is the parameter controlling the rate of the decline of the transmissivity in the soil profile (L), and q_0 represents the discharge when \bar{D} equals zero (LT^{-1}).

The functional form for the vertical drainage flux q_v (LT^{-1}) used in TOPMODEL is

$$q_v = \frac{S_{uz}}{t_d D_i} \quad (6)$$

in which D_i stands for the local saturated zone deficit (L), S_{uz} is the storage in the gravity drainage zone (L), t_d mean residence time for the vertical flow per unit of the deficit (TL^{-1}). The local saturated zone deficit is calculated from

$$D_i - \bar{D} = -m(I_i - \bar{I}) \quad (7)$$

TOPMODEL was applied to the Uhlirka catchment also by Blazkova and Beven (1997).

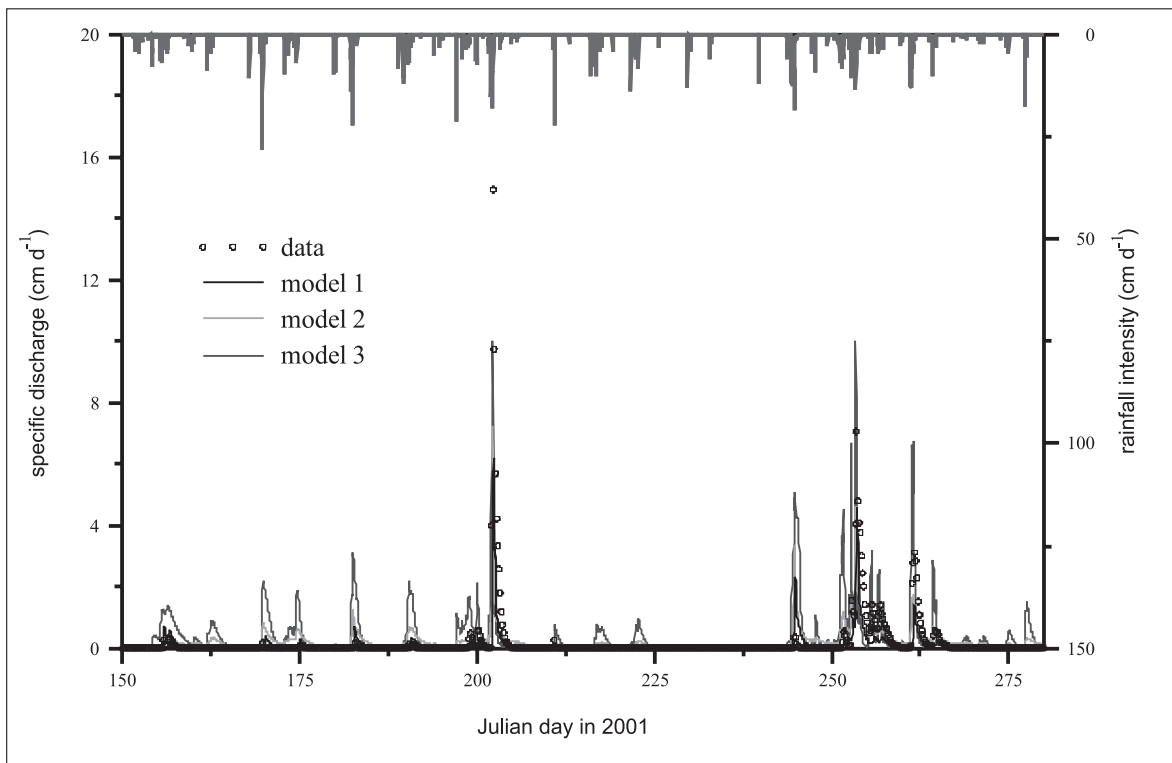


Figure 1. Specific hillslope discharge in vegetation season 2001

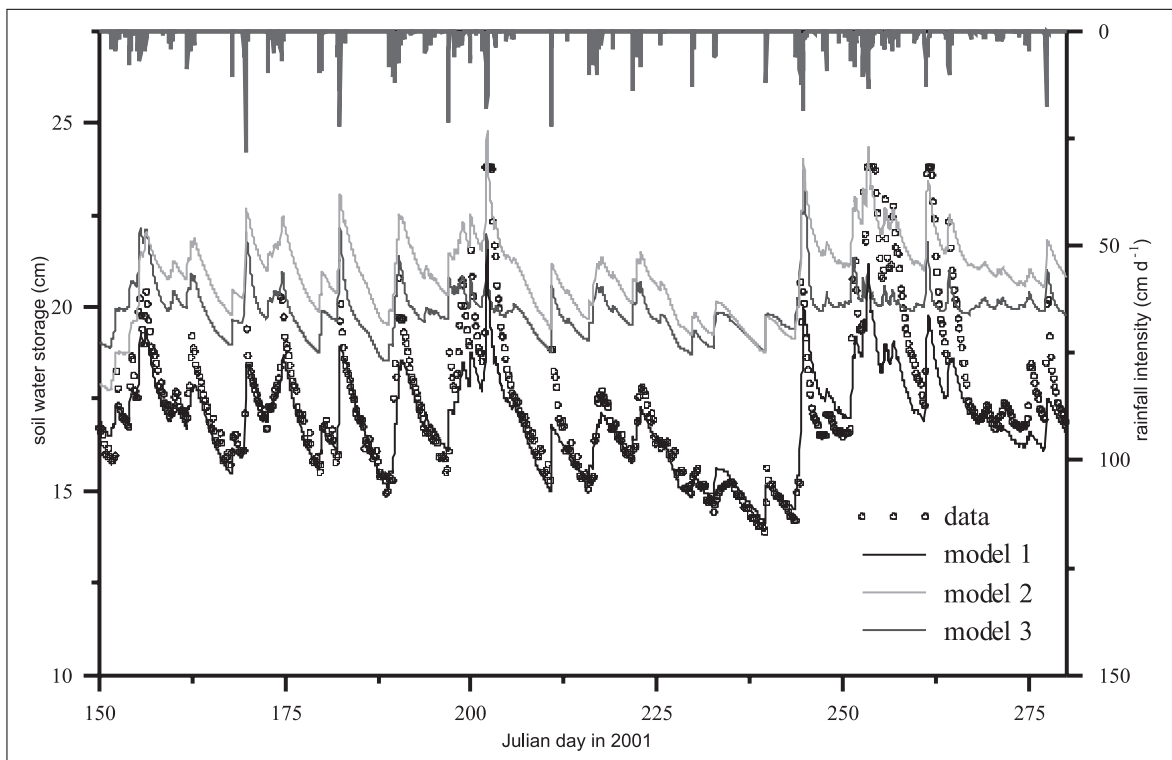


Figure 2. Soil water storage in vegetation season 2001. The values marked as “data” were calculated from the tensiometer observations

Results and conclusions

The three tested modeling approaches were applied to the data measured during several vegetation seasons. The comparison of the modeling results shows that all applied models predict relatively well the hillslope responses to major rainstorms in terms of the occurrence of the shallow subsurface runoff. However, for a number of moderate storm events, the zero-dimensional approaches (model 2 and 3) predict nonzero discharge, where no discharge was actually observed (see Figure 1). Both zero-dimensional approaches failed to predict the temporal changes of the soil water storage (see Figure 2). As expected, the soil water storage was predicted well by the physically based dual continuum model, which also performed well in estimating the occurrence of the subsurface stormflow, although it failed to provide perfect match of the measured hillslope discharge peaks.

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