Soft experiments: A new approach to study water flow and solute transport at the hillslope scale

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Introduction

Even when major hillslope experiments are undertaken in order to understand subsurface flow and transport processes (e.g. McDonnell et al., 1996), the "transference value" to even neighboring hillslopes is minimal as bedrock topography, soil properties, geometries, etc. change. Thus, while there have been dozens of field experiments in hillslope hydrology that have explored where water goes when it rains, what flow pathways the water has taken and how long that water has resided in the hillslope, each experiment is essentially "unique" in terms of results and refinement of our conceptual description (Bonell, 1998).
One possible step after having defined and refined the conceptual description of runoff generation and solute transport in hillslopes is to evaluate the main controls of these processes by conducting numerical experiments. The model can then be used as a hypothesis testing tool and consequently lead to an organizational structure of the main controls in hillslope hydrology. This paper presents such a model and organizational framework for water flow and solute transport at the hillslope scale. Our main objectives are to test how soft experiments (numerical experiments with the model driven by collective field intelligence) can be used as a way forward for structuring and clarifying the controls on flow and solute transport at the hillslope scale. Here, we test how drainable porosity influences water flux, and constrain the model's performance with event/pre-event water ratios, residence time, and tracer breakthrough.

Model description and approach

The model is based on a grid-based, quasi three-dimensional saturated subsurface flow algorithm (Wigmosta and Lettenmaier., 1994). The rate of saturated subsurface flow q at each grid cell at a time t is calculated under Dupuit-Forchheimer assumptions (Freeze and Cherry, 1979) as:

$$q(t) = T(t)\,\beta\,w \qquad (1)$$

where T is the transmissivity, β is the water table slope, and w is the width of the flow. The transmissivity is determined by the local hydraulic conductivity and the thickness of the saturated zone. The local hydraulic conductivity is parameterized by a power law depth distribution (Ambroise et al., 1996) and the thickness of the saturated zone is defined by the water balance in each grid cell. In addition to the water flow, mass transport within the saturated zone was implemented by an advective transport module from one to another grid cell and a new conceptual interaction between the saturated and unsaturated zone in order to account for the mass exchange under a changing water table (Weiler and McDonnell, 2002). This concept is based on the assumption that the proportion of the drainable porosity n_d (a term used here to describe what others have

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called specific yield and effective porosity) to the total porosity n is defined mainly by the soil water characteristic curve. Water flow through the unsaturated zone is neglected in this version of the model since the transient response from hillslopes is often via temporary saturation at the soil-bedrock interface (McGlynn et al., 2002).
In accordance to the results of a variety of different hillslope experiments, we evaluated a number of potential first-order controls on subsurface flow at the hillslope scale:

- Hillslope geometry (planar and profile curvature)
- Proportion of drainable porosity to total porosity (defined by the soil-moisture characteristic curve and thus the different soil characteristics)
- Spatial soil depth variation based on the geo-statistical properties of surveyed soil depth distributions.

The simulations were evaluated based on observations of already conducted hillslope experiments described by McDonnell et al. (1998) and Freer et al. (2002). In addition to the runoff at the base of the hillslope and water table variations in the hillslope, the results of tracer breakthrough based on a line source application, hydrograph separation in event and pre-event water, and residence time distribution of the hillslope were all simulated and compared to 'expert judgment' based upon our field experiences. These additional soft data (Seibert and McDonnell, 2002) beyond the simple fit of the outflow hydrograph were seen as an important test for judging the model's ability to work "right" for the right reasons. The boundary conditions were set to either natural recharge with multiple events or a constant recharge rate copying an artificial sprinkling experiment. Some results were directly compared with observations of hillslope experiments, but the majority of the simulations were used to analyze and rank the main controls of subsurface flow at the hillslope scale.

Results and discussion

A simple planar hillslope (160 m by 52 m, slope of 30%) was set-up within the soft experiment design. A constant soil depth (2 m) for a single constant recharge event were simulated. Figure 1 shows the multiple responses of flow and transport (rows) for three different soil classes (columns), that are characterized by a low (0.2), medium (0.4) and high (0.7) proportion of drainable porosity (PDP) to total porosity corresponding to three soil classes of loam, sandy loam, and loamy sand. The resulting subsurface runoff hydrograph was very similar for each PDP. Runoff increased during the recharge event, was then relatively constant for 8 h and then slowly decreased to pre-storm values (Figure 1a). Internal water table response differed markedly for different PDPs, where water table response was highest for the soil with the lowest drainable porosity and vice versa (Figure 1b).
Pre-event water runoff and pre-event water proportion for the three soil classes were compared. The soil with a low PDP showed a total pre-event water fraction of 81.8% with a minimum, relatively constant pre-event water contribution of 80% after 20 h. The medium PDP soil had a much lower pre-event water fraction of 59.3% and a relatively constant pre-event water contribution of 57% after 20 h. The lowest pre-event water fraction of 28.9% was associated with the high PDP soil, with a pre-event water contribution minimum of 18% at the peak of the hydrograph.
We simulated the breakthrough of a conservative tracer from the line source at 40 m distance from the hillslope base (Figure 1d). The peak mass flux and total mass recovery increased and the peak arrival time decreased with increasing drainable

porosity. However, the transport velocity for the low PDP soil was still high, with a maximum velocity of 6.6 m h^{-1}. This fast tracer breakthrough has often been questioned in field experiments if the system shows high pre-event water contribution to runoff (McDonnell et al., 1998). The tailing of the concentration breakthrough curves also indicated that mass retention in the unsaturated zone decreases if the drainable porosity increases. This effect can, on the one hand, be related to the maximum water table increase, since the mass exchange between the saturated and unsaturated zone is proportional to the water table fluctuations. Alternatively, the change of total volume of the unsaturated zone may be due to the change of the difference between total and drainable porosity.

Finally, the residence time distribution was computed for concentration, mass flux and mass recovery (Figure 1e). The mass flux was similar to the hydrograph with different absolute values for the three different soil classes. Thus, the concentration was quite constant, especially for the low PDP soil, and showed a longer tailing distribution for the high PDP soil. The final recovery rate after 80 h was strongly related to the drainable porosity. For example, for the medium PDP soil, over 50% of the water entering the saturated zone at 1 h after beginning of the simulation was still in the system after 80 h.

Modeled differences for different hillslope geometries were small compared to the

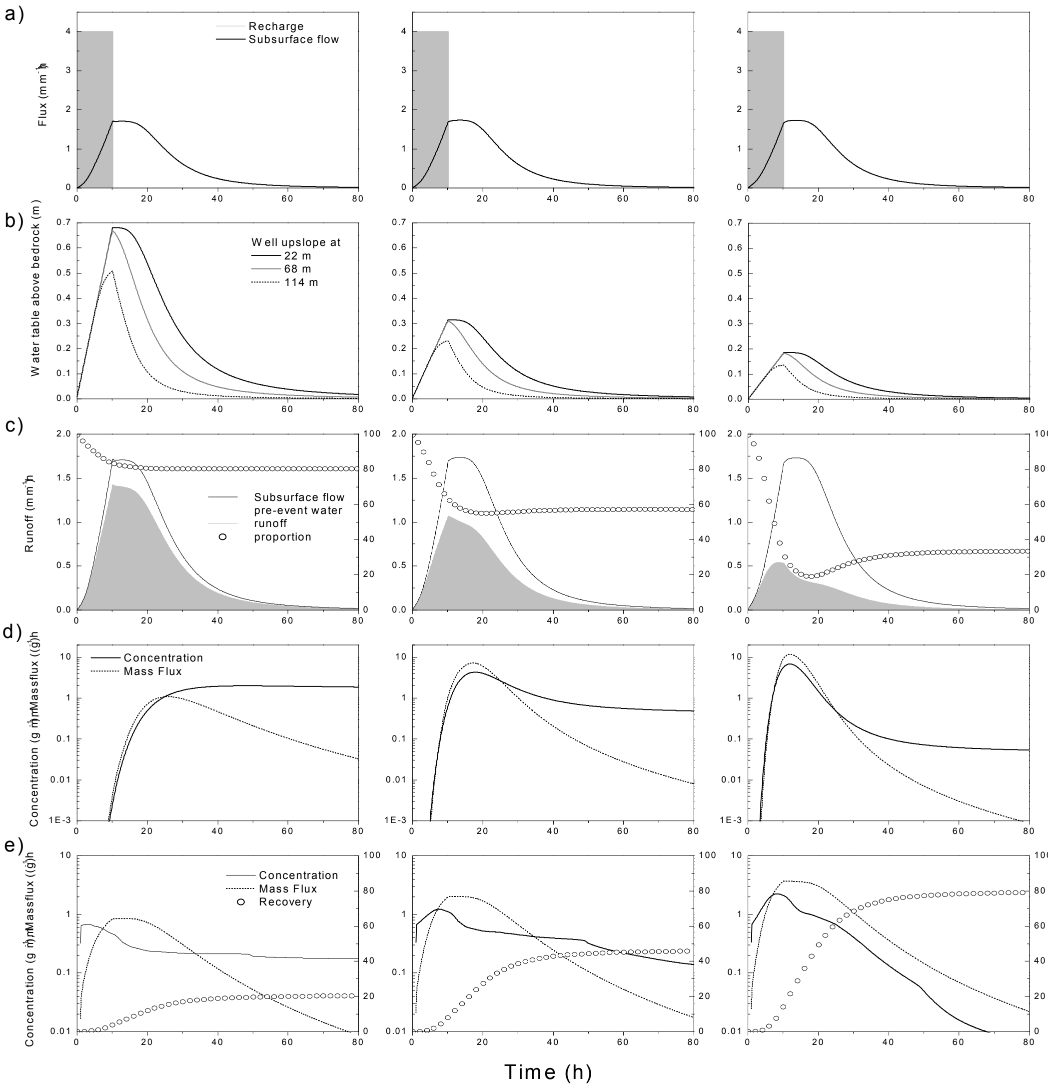

Fig. 1. Soft experiment for a planar hillslope with different PDP (columns).

differences resulting from the soil properties. However, hillslope geometry was found to especially influence the shape of the residence time distribution within the first hours and days, compared to the soil properties mainly influencing the mean residence time. Additionally the shape of the hydrograph and response of the water table in the hillslope was influenced by the hillslope geometry.
Soil depth variations in the hillslope showed prolonged influence on the flow pathways. Flow was channelized in hollows and water was retarded in depressions after the event. Additionally, commencement of runoff was often later and the hydrograph rose slower, as the flow network in the hillslope became established. At the base of the hillslope, a high spatial variation of the hydrographs was observed, similar to observations on natural hillslopes (McDonnell et al., 1996; Freer et al., 2002). The resulting flow pathways in the hillslopes with higher fluxes relative to the neighboring cells produced a distinct spatial pattern of variations in tracer mass storage after the event. This pattern then exerted a first order control on event water proportion and residence time.

Conclusions

The main controls of subsurface flow and transport at the hillslope scale were evaluated using a conceptual hillslope model in a soft experiment framework. The evaluated controls were based on our experiences of various hillslope experiments. The results of the simulations were also compared with contrasting observations of hillslope experiments including flow, residence time, old/new water ratios and residence time. Our results indicate that the shape of the hydrograph is controlled mainly by the hillslope geometry and the depth function of the soil transmissivity. Drainable porosity controlled transport and the resulting event water contribution, breakthrough of tracer, and residence time distribution. Finally, water flow and transport can be highly spatially variable if the soil depth and thus the bedrock topography show a spatial variability.

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