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Numerical experiments on the sensitivity of runoff generation to the spatial variation of soil hydraulic properties

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Abstract

Spatially distributed soil hydraulic properties are required for distributed hydrological modelling. These soil hydraulic properties are known to vary significantly in space, and considering the non-linearity of runoff generation, the question arises how the spatial variation of soil hydraulic parameters affects the continuous runoff modelling for a micro-scale catchment. This was analysed by applying a three-dimensional hydrological model to the 28.6 ha 'Berrensiefen' catchment, Germany, for a simulation period of one year. The model was based on an observed distribution of soil hydraulic properties, which were assumed to be layered in vertical and to vary continuously in horizontal direction, and validated for total runoff. Numerical experiments with five spatial distributions of soil hydraulic parameters derived from the observed spatial distribution, which was supposed to be the 'true' underlying spatial variation, were carried out. These five spatial concepts were: choropleth map, spatially homogeneous case, random distribution, stochastic simulation and conditional stochastic simulation. The comparative modelling revealed a significant sensitivity of runoff generation towards the spatial variation of soil hydraulic properties. The comparison of the hydrograph of surface and macropore runoff to the initial model runs exhibited the highest root mean square error with 1.3 mm h^{-1} for the homogeneous case. Further we detected, that the frequency distribution of soil hydraulic properties played an important role for the reproduction of runoff amounts. But also the spatial topology (deterministic spatial variation) was relevant for an adequate description of runoff generation. Conditional stochastic simulation is seen as a promising approach, because it preserved both, the frequency distribution and the deterministic variation.

Keywords: Conditional stochasic simulation; Soil mapping; Macropore runoff; Soil hydraulic properties; Spatial variation; Soil heterogeneity

1. Introduction

The spatial arrangement of soils, topography, geology and land cover determines the spatial pattern of hydrological processes (Grayson and Blöschl, 2001). The spatial data used for hydrological modelling are often treated as variables with discreet spatial units of averaged parameter values (Zhu and

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Mackay, 2001). Such kind of a spatial concept might be suitable for several variables, like e.g. a classified land cover. Nevertheless, the question arises, whether such a spatial concept is appropriate for the spatial pattern of soil properties (Burrough, 1993; Webster, 2000; Heuvelink and Webster, 2001) and in particular for soil hydraulic parameters. These are known to vary significantly in space (Warrick and Nielsen, 1980; Vereecken et al., 1997) and to strongly affect hydrologic processes such as runoff generation. Soil parameters show a distinct layering in the vertical direction, allowing for a spatial concept of discrete boundaries. But soil properties are assumed to vary continuously in the horizontal direction. The question arising now is: How does the spatial aggregation of soil hydraulic properties in horizontal direction affect the hydrological response? This is particularly relevant against the background of the non-linear relation between soil parameters and water fluxes (Beven, 2001). Here the upper part of the unsaturated zone plays an important role for the runoff process by splitting up the precipitation into two fractions: infiltration and infiltration excess, which becomes surface runoff (Hortonian overland flow) or macropore runoff.

The significant influence of the spatial variability of soil moisture as an initial condition for an event based modelling of runoff was already investigated in detail (Merz and Plate, 1997; Bronstert and Bardossy, 1999; Zehe and Blöschl, 2004). Seyfried and Wilcox (1995) distinguished between deterministic and stochastic spatial variability and pointed out that often geostatistical methods were applied capturing the stochastic variability but neglecting the deterministic variability. This distinction between stochastic and deterministic variability was taken up by Merz and Bardossy (1998). They used an event-based model to determine the effect of the spatial variability of the water content at saturation and the saturated hydraulic conductivity on runoff and detected, that a structured (deterministic) variability created larger runoff amounts than a purely stochastic variability. Loague (1988); Loague and Corwin (1996) used a Monte-Carlo approach for the spatial variability of the saturated hydraulic conductivity of a synthetic hillslope and proved a high relevance of this parameter for the description of infiltration processes. Loague and Kyriadikis (1997) applied stochastic simulations (Sequential Gaussian Simulation) for a small catchment to capture the spatial variation of saturated hydraulic conductivity. This approach led to a slightly improved runoff prediction compared to simulations using saturated hydraulic conductivities obtained by simple averaging or by kriging.

Due to the computational effort three-dimensional water flow modelling applications for catchments are still rather sparse. The first layout for a three-dimensional model of unsaturated water fluxes was developed by Freeze (1971). First three-dimensional catchment modelling was enabled by codes like SHE (Abbott et al., 1986) or IHDM (Beven et al., 1987). Binley et al. (1989a) developed a three-dimensional finite element model and applied it in a first step to a synthetic hillslope (100×150 m) with a spatially variable hydraulic conductivity. In the second step Binley and Beven (1992) applied this model for a 25 ha catchment with a homogeneous saturated hydraulic conductivity in horizontal direction. This model system was further developed by Paniconi and Wood (1993) and was applied to a micro-scale catchment of 24 ha size with a 30 m grid in horizontal direction. A more recent development is the event-based HILLFLOW3d (Bronstert and Plate, 1997), which was used to model the variably saturated water fluxes under consideration of macropores for a 33 ha catchment. To demonstrate the uncertainty in initial soil water contents for event-based runoff simulations, Loague et al. (2005) applied the 3d Integrated Hydrology Model (InHM; VanderKwaak and Loague, 2001) to the 10 ha R-5 catchment. An overview of selected physically-based models related to near-surface hydrologic-response processes is given by Loague and VanderKwaak (2004).

In this study SWMS_3d (Šimůnek and Huang, 1995) was extended by a macropore runoff submodel. A runoff delay routine was applied to continuously model the hydrological processes of a 28.6 ha catchment for one year. This model, using a continuous spatial structure for the hydraulic properties of two soil horizons, was validated against measured runoff. The spatial structures of soil hydraulic properties were derived from a point data set on soil textural properties in combination with a pedo-transfer function and in dependence of terrain attributes using regression kriging (Herbst et al., 2006). Using this observed spatial structure as the