Hydrological flow processes:

From micropore to catchment

Habilitation Thesis
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Overview

The material presented here is organized in five parts that encompass the research activity of the author:

I **Introduction**

II **Soil physics**
  Principles and mechanisms of the dual porosity modeling
  Application to particles and iodide transport

III **Land use and soil management**
  Application in agricultural soils

IV **Soil hydrology**
  Temporal up-scaling of soil hydrological processes
  Spatial up-scaling of soil hydrological processes

V **Conclusions and perspectives**

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Introduction

Preferential flow is well recognized as a potentially important infiltration mechanism in soils because it may increase the leaching potential of soils, resulting in the accelerated transport of nutrients, pesticides, and pathogens (e.g., Jarvis, 2007; Köhne et al., 2009a; 2009b). Preferential flow of infiltrating water in macropores may bypass most of the soil porous matrix (e.g., Beven and Germann, 1982) and limit the storage, filter, and buffer functions of soils (e.g., Clothier et al., 2008). Macropore flow is a subset of preferential flow that occurs in continuous root channels, earthworm burrows, fissures, or cracks in structured soil (e.g., Gerke, 2006; Hendrickx and Flury, 2001). Its initiation during infiltration depends on the initial matrix water content, intensity and amount of rainfall, matrix conductivity, and soil surface contributing area (e.g., Jarvis, 2007; Köhne et al., 2009a, 2009b).

Although their fraction of the soil pore volume is restricted, macropores are reported to transport most of the water and solutes under specific soil conditions. For example, Alaoui and Helbling (2006) have reported that for an estimated macropore volume of only 0.23 to 2% of the total soil volume, macropores transported 74 to 100% of the total water vertically downwards. In another study, Lin et al. (1996) have shown that just 10% of the soil porosity (macro- and mesopores) contributed 89% of total water flow. As already demonstrated in an untilled soil by Ehlers (1975), the maximum infiltrability of conducting channels can exceed 60 mm h^{-1}, although the volume of these channels may total only 0.2% of that of the soil.

Although vertical preferential transport has been investigated intensively over the last two decades, less attention has been paid to exploring the relationships between vertical preferential flow and runoff processes occurring at hillslope scale. Scherrer (1996) carried out sprinkling experiments on grassland and arable land in regions of Switzerland with soils of different geological origin. Due to their heterogeneity, natural soils respond to rainfall in many ways (Scherrer et al., 2007). Despite the progress in developing new approaches (Troch et al., 2002) and field investigations (Scherrer and Naef, 2003) on hillslope hydrology, there have been only few attempts to include preferential flow in the model’s structure (Weiler and McDonnell, 2007). Moreover, hydrodynamic aspects in terms of storage capacity have to be compared between grassland and forest soil since no clear tendency could be concluded from the existing literature on this topic (e.g., Badoux et al., 2006). The present study is motivated by the need to develop methods that support predictive modelling of the impact of macropore flow on the overall flow processes occurring at the landscape scale under different field slopes and two different vegetation types.

At plot and hillslope scale, many different aspects of runoff formation have been studied in recent years (e.g. Anderson and Burt, 1990; Buttle and McDonald, 2002, McDonnell, 2003; Scherrer et al., 2007). To integrate this process knowledge in rainfall-runoff models, information is needed to define the spatial distribution of the runoff processes in the catchment under consideration. For this purpose, methods based on soil data, geology, topography and vegetation for process identification have been developed to delineate dominant runoff processes or zones of predisposition to produce runoff at plot scale (e.g., Peschke et al., 1999; Scherrer and Naef, 2003; Markart et al., 2004). Similarly, Maréchal and Holman (2004) used the Hydrology of Soil Type (HOST) system (Boorman et al., 1995) to provide a conceptual representation of hydrological processes in UK soils. Their model defines the hydrological behaviour of soils in terms of their influence on river flow at the catchment scale and gives a classification of all the soil types of the United Kingdom into 29 conceptual response models (or classes). Based on a similar method, and with the help of sprinkling experiments, Schmocker-Fackel et al. (2007) produced maps of the dominant runoff processes that show the potential of each area to produce a given runoff process.

All the methods used for this purpose are limited because they do not quantify the hydrodynamic aspect of flow processes in time and space scales and fail to establish the hydrologic connectivity between the established zones of predisposition. Therefore, there is a need of investigating the complex interaction between soil vegetation, field slope, soil clay content and initial soil moisture before establishing schemes for up-scaling the flow processes to the catchment scale (Alaoui et al., 2010a).

In catchment hydrology, it has been shown that for runoff generation processes, the use of measured in-situ parameters cannot be expected to produce accurate predictions at all scales, because of the non-linearity of the processes involved, together with the heterogeneity of the natural system (Beven, 1995). One way to overcome this drawback is to investigate the channels to which flow converges and that are characterized by a structured correlation due to a smoothing effect, by using, for example, Terrain analysis with Digital Elevation Models (TauDEMs) (Tarboton, 1997). The specific catchment area contributing to flow at any particular location is useful for determining relative saturation and runoff generation from saturation excess in models such as Topmodel (Beven and Kirkby, 1979; Beven et al., 1984; Wood et al., 1990).

TauDEMs are appropriate methods to generate high resolution maps of flow network. Digital data generated by this approach also have the advantage that they can be readily imported and analyzed by Geographic Information Systems (GISs). The technological advances provided by GISs and the increasing availability and quality of Digital Elevation Models (DEMs) have greatly expanded the potential application of TauDEMs to many hydrologic, hydraulic, water resources and environmental investigations (Moore et al., 1991). The continuity of the DEM is an important contributor to interpolated gradient values, potentially affecting energy estimates as well as flow directions (Tarboton, 1997).

The experimental evidence showed that up-scaling hydrological flow processes from plot to catchment scale is a challenging task because of the gap between quantifying soil structure and predicting the impact of structure on water and solute transport at the landscape scale. This can be addressed by integrating classical pedological approaches to describing soil-landscape patterns with process knowledge gained from soil physics and hydrology. The present habilitation thesis tackles some of the difficulties inherent in addressing such a complex issue.

The main steps followed to achieve the goal of integration were:

- Identification of flow processes using appropriate experimental designs and models to better assess all process aspects (soil physics).
- Definition of the scope of the models used and of their limitations with regard to application under different conditions (land use and soil management).
- Improvement of these models / approaches to extend their application at the temporal and spatial scales (soil hydrology).

Special attention was given to both experimental and modelling aspects with respect to preferential flow.

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