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Characterizing soil water dynamics on steep hillslopes from long-term lysimeter data

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SUMMARY

Understanding soil water dynamics on hillslopes is of crucial importance to the prediction of floods and other hydrological events in mountainous catchments, to the identification of natural vegetation patterns, and to the optimization of agricultural land use. In principle, such information can be obtained from lysimeters, but most experimental lysimeter facilities have been installed on flat terrain. This study presents a long-term and high-resolution investigation of soil moisture, surface and subsurface flow using three large-scale lysimeters on a slope with 23.5° inclination on a landfill site in Karlsruhe, Germany. Data from a 10-year observation period were evaluated for this study, including weekly soil moisture data obtained by neutron probes, continuous discharge data from the land surface and several layers within the soil zone, and hydrometeorological data from a climate station. The results reveal (i) clear temporal and spatial patterns of soil moisture variations down to a depth of 250 cm, (ii) substantially higher discharge and faster percolation rates in the lower part of the lysimeter field, indicating significant downhill flow at various depths within the soil profile, (iii) characteristic threshold values for flow processes in the soil, associated with a hysteresis effect between soil moisture and flow processes. These results can be used as a basis of improved numerical models for the simulation of floods, soil moisture distributions, and vegetation patterns.

1. Introduction

Soil water dynamics plays a decisive role in flow and infiltration processes. This dynamics has a high variability on steep slopes, which is caused by short-term extreme precipitation events or wet periods on a long-term scale. Long-term time series of moisture dynamics, however, are still rather rare (or in the process of being collected). Lysimeters are appropriate experimental facilities for the quantification of surface/subsurface discharge and the dynamics of soil moisture change.

When soil moisture and discharge are observed continuously, assertions can be made with respect to wetting fronts and subsurface flow patterns. Various hydrodynamic parameters influence the characteristics of water movement in the unsaturated zone, such as field capacity, heterogeneity, sub layering, matrix potential, unsaturated conductivity, preferential flow paths, antecedent moisture, hydraulic potential, and pore connectivity (Hiscock, 2005; Morbidelli et al., 2011, 2014; Zhou et al., 2012). Additionally, temporally and spatially detailed data of fluid flow and moisture movement in the unsaturated zone are important with regard to contaminant transport and storm water discharge (Goldsztein, 2008; Phi et al., 2013).

Kim (2012) measured soil moisture over a time period of one year at a catchment to investigate the spatio-temporal correlation between hillslope and topography. Tromp-van Meerveld and McDonnell (2005) measured soil moisture across a hillslope at various depths to analyze the influence of small-scale variations on the water balance of a catchment. They found a spatial influence of topography on soil moisture in a state of transition from dry to wet only. Mahmood et al. (2012) used soil moisture data of 41 stations from 1999 to 2004 to investigate the influence of soil moisture on land-surface–atmosphere interactions. Here, cross-correlations between various soil depths (10/25, 10/50, 10/100, in cm) were made. Jasper et al. (2006) investigated changes in soil water behavior in relation to climate change, with the warm summer of 2003 being used as an example.

Hewlett and Hibbert (1963), McCord and Stephens (1987), and Torres et al. (1998) made field observations of lateral flow in a hillslope. A number of laboratory sand tank experiments propose a rather lateral flow at the top and the bottom of the profile and a more vertical flow in between (Anderson and Burt, 1977; Lee et al., 2011; Lv et al., 2013; Phi et al., 2013). Sinai and Dirksen (2006) watered homogeneous sand with a v-shaped surface and

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used dyes to portray the moisture streamlines. They observed "uphill flow" (according to Zaslavsky and Sinai, 1981) due to matrix potential gradients, where the wetting front percolated not vertically, but rather perpendicular to the surface. During steady rainfall, the percolation direction changed to a vertical and during the drainage phase, to a more parallel direction. The behavior of infiltration rates on sloping surfaces was analyzed by Chen and Young (2006), Essig et al. (2009) and Morbidelli et al. (2015) comparing numerical models and laboratory experiments.

Another important issue is whether there are distinct initial soil moisture thresholds that trigger discharge. Soil discharges water, when it exceeds field capacity. But other aspects have to be taken into account as well, such as macro pore flow or a sudden rise in pore pressure due to an intensive pulse of rain (Torres et al., 1998). Zehe et al. (2010) suggested maximum energy dissipation through mass inflow (rainfall) and connected worm burrows.

Most of the above-mentioned studies used soil moisture data determined by time domain reflectometry (TDR) or capacitance techniques. In this study, soil moisture contents were obtained by the neutron scattering technique (Evett and Steiner, 1995). This technique can be used at much larger depths (up to 3.2 m = max. depth of measuring points) and has a higher reliability in clayey soils than TDR measurements, where a dependence of the dielectric constant on temperature has to be taken into account (Pepin et al., 1995; Hook and Livingston, 1996; Sun et al., 2000).

Since the data cover more than 10 years of measurement, a large range of climatic conditions is covered, including the very dry summer of 2003 and several wetter periods. Within the framework of this study, an attempt was made to determine the range of the initial soil moisture leading to drainage. Furthermore, a comparative analysis of the soil moisture profiles of three adjacent measuring points was carried out to illustrate the propagation of moisture, but also to depict non-vertical downhill moisture movement. This was done in high vertical resolution (cross-correlations from 10 to 220 cm soil depth), but with less detailed temporal resolution compared to Mahmood et al. (2012). The two-part construction of the test site presented here provides a unique insight into the quantities of lateral flow under field conditions.

2. Material and methods

2.1. Experimental site

The lysimeter test site is located on the Karlsruhe-West landfill, in the north-western part of Baden-Württemberg, Germany (Fig. 1a). The large-scale lysimeter is embedded into the surface sealing system of the landfill. It describes an angle of 23.5°. The experimental site consists of two fields (field I and field II) (Fig. 1a) with slightly differing thicknesses of layers (see Table 1 for more detail). Field II comprises 2 compartments, field IIA and field IIB. For this study, the focus is on compartment IIB (Fig. 1b), since the soil moisture measurements using the neutron probe cover a larger area. Until 2012, the measuring points NP5 to NP7 were used in field IIB. In August 2012, point NP8 was added to the monitoring program. The uppermost restoration layer (RL) is most important in terms of water storage and evapotranspiration. When the storage capacity is exceeded, the drainage layer (DL) starts to discharge. The underlying mineral clay liner (MCL) is the sealing component. The last segment is the capillary barrier with the capillary layer (CL) and the underlying capillary block (CB). The overall depth of field IIB ranges from 2.75 m for the lower slope to 3.25 m for the upper slope. Taking the slope into account, lysimeter field IIB covers a horizontal area of 183.4 m^2. The bottom and the edges of the field consist of a high-density polyethylene canvas. In total, 4 steel tubes of 40.5 mm in inner diameter are installed for neutron probe moisture measurements, two tubes in each slope. The tubes end approximately in the capillary layer in the upper slope and at the top of the capillary block in the lower slope. The grass cover of the field is evenly distributed; sheep are held to occasionally graze on the field to keep the vegetation low. Hereinafter, a prefixed *U* describes the upper slope (e.g. UDL: Drainage layer of the upper slope) and a prefixed *L* denotes the lower slope (e.g. LDL: Drainage layer of the lower slope).

2.2. Discharge collection

The discharge of the layers is collected at a control station further downhill (Fig. 1a). In total, 13 discharge pipes lead to the station and drain into purpose-built cylindrical polyethylene containers. The water levels are continuously monitored by custom-made pressure sensors (BD Sensors GmbH). They monitor water level changes of 2 cm, threshold values (i.e., 85 cm or 15 cm), or, when no change is imminent, regularly every 15 min with an accuracy of 0.1%. When the upper threshold of 85 cm is reached, a valve opens; water leaves the container and flows to the landfill percolation water treatment facility. At a minimum water level of 15 cm, the valve closes. The water containers have different diameters (from 12.9 to 30.8 cm) depending on the flow rate of the discharging layer. Flows of layers with a large drainage volume, such as surface flow or flows from the drainage layer (>100 L h^{-1}), are passed to containers with a larger diameter than those for the capillary block (<5 L h^{-1}), for instance. The data are saved in custom-made wireless data loggers for standard signals.

2.3. Rain gauge

Fig. 1a shows the location of the rain gauge at the bottom of lysimeter field I. It is installed on ground level to measure the precipitation directly at the lysimeter surface. The measuring method of this gauge is based on the weighing principle. Any precipitation event is registered by an increase in weight. An incorporated precision amplifier provides measurements with a resolution of 0.01 mm at an effective range of 250 mm (OTT Hydromet, 2003). Additionally, a climate station at the top of the landfill was operated by the municipal waste management company (until 2013). This station measured wind speed and direction, air humidity, solar radiation, and precipitation.

2.4. Soil moisture measurement

Soil moisture measurements are carried out using two probes. Until August 23, 2012, measurements were done with a modified Wallingford IH2 probe. Since November 30, 2012, measurements have been conducted with a modified Troxler model (4300 Depth Moisture Gauge). Both probes have Am/Be sources with activities of 1.85 GBq (Wallingford) and 370 MBq (Troxler), respectively. For more than 10 years now, soil moisture has been measured on a weekly basis and occasionally more frequently during rain events.

The measurement points are shown in Fig. 1 (NP5–NP8). Moisture is measured down to a depth of approx. 2.8 m in the lower slope and approx. 3.2 m in the upper slope at intervals of 10 cm. The Wallingford probe was calibrated at a sand dam with gravimetric moisture measurements in the laboratory by Gerlach (2007). The Troxler probe was field-calibrated by using the Wallingford probe. The resulting mean standard deviations for the Wallingford probe are 0.18 at NP6 and 0.4 at NP7 and for the Troxler probe 0.26 (NP6) and 0.36 (NP7), which is well within the instrument specifications (Troxler Electronic Laboratories, 2006).