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Matrix and bypass-flow in quaternary and tertiary sediments of agricultural areas in south Germany

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Abstract

In hilly areas of south Germany with tertiary and quaternary sediments, percolation has been studied applying an isotope tracer of the water molecule in small-scale field experiments to better understand the hierarchies and interconnections of quick and slow seepage. On a catchment-related scale, these results have been connected with traditional and environmental isotope analysis of discharge to better quantify quick and slow seepage components, and to better assess the export of agrochemicals into ground- and surface waters. Consequently, the development of improved application techniques of agrochemicals and better strategies for ground and surface water protection is possible. The unsaturated zone of the study area was traced with Deuterium on areas of about 50 m^2. Results show that infiltration splits into bypass and matrix-flow. Bypass-flow exceeds flow velocities of 0.5 m day^{-1}, which is close to flow velocities of overland-flow, and matrix-flow ranges between 0.7 m $year^{-1}$ (Loess) and 1.2 m $year^{-1}$ (Tertiary gravels and sands). In these unconsolidated rocks, bypass-flow seems to (1) be strongest under wet and dry conditions at the soil surface; (2) be more dominant in coarse than fine-grained sediments; (3) be more pronounced in terrestrial than in marine sediments; and (4) penetrate to an average depth of less than 1 m in fine-grained sands and silts, and deeper than 3 m in gravels before it either finally incorporates into matrix-flow or generates interflow. Hydrographic analysis shows that more than 21% infiltration produces interflow by the transformation of bypass-flow into lateral flow, and about 75% infiltration groundwater recharge; 4% of bypass-flow incorporates into matrix-flow. In the study area, plowing techniques and field size influence significantly and proportionally the distribution of overland- and interflow-flow. However, groundwater recharge is not significantly changed. As matrix-flow is too slow an indicator to clarify how changes in land use affect groundwater quality over time, the analysis of direct discharge may be considered a good early indicator to assess land use changes on the export of agrochemicals.

Keywords: Matrix and bypass-flow; Inhomogeneous seepage flow; Interflow; Groundwater recharge; Land use

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1. Introduction

The unsaturated zone between land and groundwater surface has a limited regulatory function for water discharge and the fate of contaminants on their way to water resources. The main pools of contaminants are waste disposals and the effective root zone of arable soils. At the interface atmosphere and lithosphere, precipitation produces overland-flow and partly evapotranspirates. The infiltrating water is either stored or percolates to neighboring compartments as groundwater recharge or interflow (Fig. 1). These discharge components transport pollutants either dissolved or bound on particles (Seiler and Hellmaier, in press), and may thus exert adverse impacts on ground and surface waters.

Porous media often exhibit a variety of natural heterogeneities, such as shrinking cracks, macropores, interaggregate pores, as well as destruction features from humans, animals and plants. All these structures close to the land surface may affect water and solute movement at the macroscopic level by creating widely different flow velocities, often referred to as slow matrix (Hillel, 1971; Feddes et al., 1988), and fast preferential or bypass-flow (Scotter, 1978; Beven and German, 1982; Germann, 1990; Van Genuchten, 1994). These phenomena have been studied in structured (Beven and German, 1982) and seemingly homogeneous coarse-textured soils (Glass et al., 1989; Baker and Hillel, 1991). Fast flow leads to an apparent non-equilibrium situation with respect to the pressure head or the solute concentration (Wang, 1991), and severely limits our ability to define initial boundary conditions of flow, and to reliably forecast contaminant transport in unsaturated media.

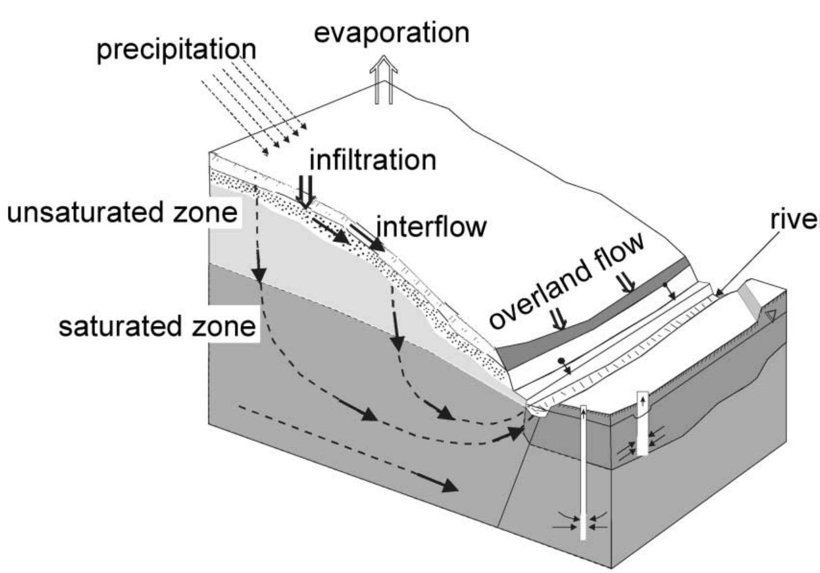

Fig. 1. Schematic diagram of a landscape with the four most important discharge components (evaporation, overland-flow, interflow and groundwater recharge).

Bypass-flow interacts with matrix-flow by means of diffusion and incorporation into the matrix, or produces interflow in hilly terrains. However, the following questions remain poorly understood: (1) how much of the infiltrating water consists of bypass-flow? (2) What is its penetration depth with respect to sediment type, weathering history, bioturbation, shrinkage and swelling, and the intensity of the infiltration process itself? And (3) how is its interaction with matrix-flow governed by capillary force gradients and the respective hydraulic conductivities or by surface tensions along solid surfaces prevailing under dry weather conditions before the infiltration event? Both these factors may prohibit or favor the incorporation of bypass- into matrix-flow at very low or high pre-existing water contents, respectively.

In order to clarify some of these questions, several Deuterium tracer experiments were conducted at natural lysimeter installations to analyze different flow components and to quantify the individual components of the flow through discharge analysis in the catchment.

2. Method of determination of bypass-flow

In field experiments, areas of melting snow covers ranging from 50 to 100 m^2 were traced with Deuterium (^2H). The ^2H-tracer is non-reactive, does not undergo significant isotope fractionation in winter (low evaporation) and does not change the ion balance of soil water. Deuterium break-through has been observed in natural lysimeters (Fig. 2) at 10, 20, 50, 90, 130 and 180 cm below the traced surface using three suction cups at each observation depth.

Suction cups were positioned at the end of 2-in. drilling tubes, located 3 m horizontal distance from an accessible vertical shaft (Fig. 2). Each drilling tube extended 2.7 m from the shaft opening and the conditioned suction cup was attached at the end, where a 0.3-m clearance from the free-standing pre-drilled hole existed. The three cups at each depth were positioned at a horizontal distance of 0.5 m from each other.

Water from the unsaturated zone was sampled applying suction which exceeded the prevailing tension in the respective depth by about 100 h Pa; the prevailing tension was recorded from a shaft installation 5 m distant from each water sampling shaft. Water sampling was performed individually at each suction cup most of the year. Cumulative water sampling was necessary only during very dry weather conditions. The $^2H/^1H$ ratio was measured by mass spectrometry and concentrations are expressed as per mil deviations from the international standard V-SMOW (Vienna-Standard Mean Ocean Water, vstd).

$$\delta\,^2\mathrm{H} = \frac{^2\mathrm{H}/^1\mathrm{H}_{\mathrm{sample}} - {}^2\mathrm{H}/^1\mathrm{H}_{\mathrm{vstd}}}{^2\mathrm{H}/^1\mathrm{H}_{\mathrm{vstd}}}1000 \qquad [‰]$$

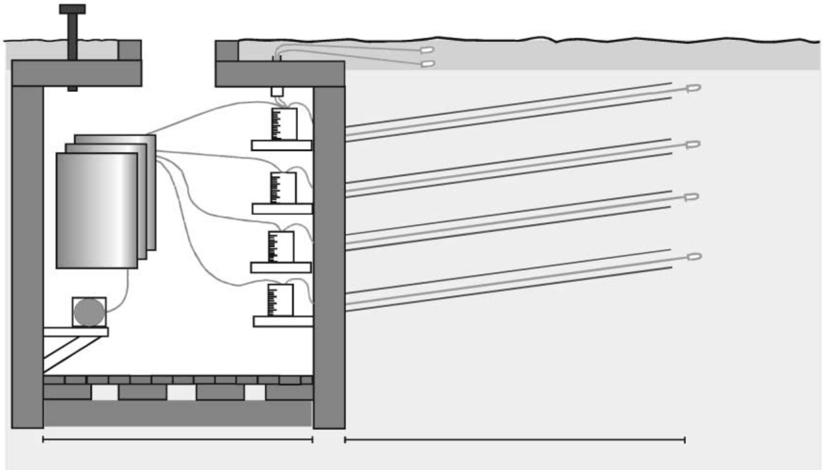

Fig. 2. Design of a natural lysimeter with suction cups, located 3 m away from the shaft wall in the unsaturated zone. At each depth, three suction cups at horizontal distances of 50 cm were installed in the 30-cm free-standing end of a tubed horizontal borehole.

whereby negative δ values indicate lower concentrations than the standard and vice versa.

3. Results on bypass-flow and interflow

Tracer application was performed once at each of eight sites in Scheyern from 1995 to 1998, and the movement of tracer in these experiments was observed throughout 3 to 4 years in three replicates at each depth. Over the melting snow, covering areas from 50 to 100 m^2 over Loess, sand and gravelly sand, tracing produced instantaneously for percolation water a Dirac signal along a hydraulic potential plane. Applying the well-known advection dispersion theory (Freeze and Cherry, 1979), homogeneous flow caused a transformation of the Dirac signal into Gaussian distributions of the concentrations at defined time steps throughout the extent of the profile. However, this had never been observed in eight experiments performed in this study (Fig. 3). The evaluation of tracer break-through curves clearly demonstrates that flow in the unsaturated zone is not homogeneous. On the contrary, it is dominated by different forms of slow matrix-flow, superimposed at the beginning of the tracer experiments by positive and thereafter by negative peaks in the break-through curve (Fig. 4), which must be attributed to bypass-flow. The observation (Fig. 4) and interpretation of Deuterium break-through at similar or different depths (Käss, 1998) clearly documents the absence of homogeneity in the flow.

It becomes evident from Deuterium break-through curve experiments that matrix-flow ranges from 0.7 to 1.2 m $year^{-1}$ in Loess and Tertiary sands/

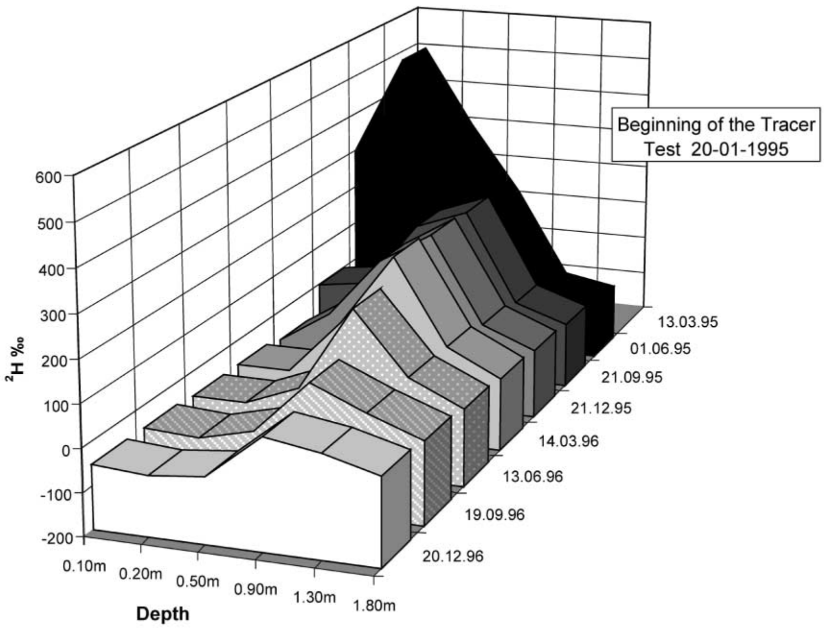

Fig. 3. Concentration distribution of Deuterium throughout the profile at given time intervals.

gravels, respectively. Infiltration ranged from 150 mm year^{-1} in the Loess to 200 mm year^{-1} at the Tertiary sand/gravel site. Contrary to matrix-flow, bypass-flow ranged between 0.7 and 2 m day^{-1} in all sediments analyzed and

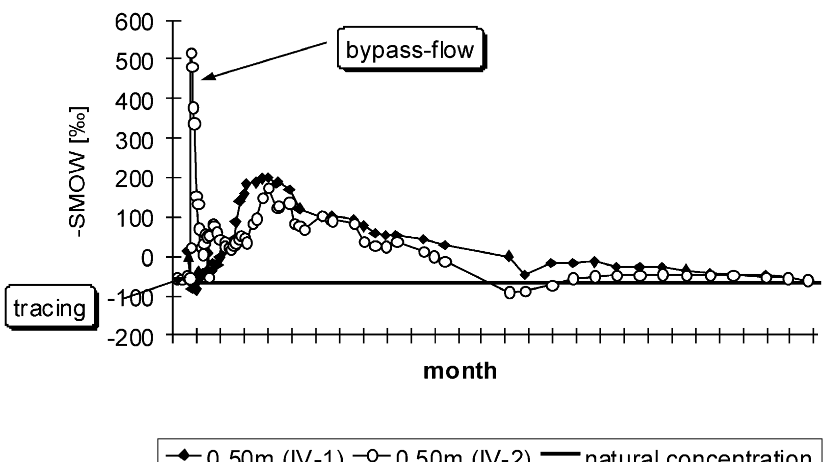

Fig. 4. Break-through curves of Deuterium, observed by extracting water from the same sampling depth through three suction cups 50 cm distant from one another, documenting slow matrix and fast bypass-flow in Loess.

thus approached flow velocities of overland-flow. Furthermore, it was observed to depths of 1 m in Loess, 1.5 m in Tertiary sands and deeper than 3 m in Quaternary gravels.

Standard calculations of seepage velocities based on tensiometer and TDR observations recorded 5 m distant to water sampling sites could hardly differentiate between slow and quick flow. Such a differentiation, however, would be possible through ^{2}H experiments, if tracer concentrations in the break-through exceed the mean of natural annual ^{2}H concentrations by at least two orders of magnitude. This is the same case since bypass-flow contributes only minimally to matrix-flow at each individual infiltration event.

Mathematical modeling has applied bypass-flow results to the generation mechanism of discharge components (interflow and groundwater recharge), and these have been quantified on a larger scale, analyzing the discharge from transient and perennial creeks in the catchment. The analysis of discharge was based on (1) hydrographic methods to distinguish between direct and indirect runoff, and (2) on the analysis of the natural environmental stable isotope information during storm events. These methods allow the calculation of mixing ratios between storm and pre-storm waters (Sklash et al., 1976) and differentiation between contributions of interflow to overland discharge having similar flow velocities, both contributing to direct runoff.

Seiler and Baker (1985) have shown that permeability changes along interfaces may favor lateral flow of seepage, according to the inclination of the interface and the differing hydraulic conductivities along it (capillary barrier concept). During storm events, such interfaces transform fast seepage-flow into fast interflow in hilly terrains, and thus, enhance direct runoff. Most of these interfaces are of anthropogenic, rock dilatation, or in the environment of formerly glaciated areas, of permafrost origin and parallel morphology. Hydrographic analysis has demonstrated, on the catchment scale of the study area, that discharge (200 mm year^{-1}) produces approximately 21% and 75% of direct and indirect runoff, respectively. Analysis of direct discharge using environmentally stable isotopes yields less than 7% of overland-flow, equivalent to the isotope signature of precipitation, and greater than 14% of interflow, equivalent to the isotope signature of matrix-flow in areas lacking base-flow. The remaining 4% of runoff is interpreted as bypass-flow that joins matrix-flow.

The mean annual interflow greater than 14% varied between zero and over 60% of infiltration, and depended on initial hydraulic conditions at the soil surface, as well as on the intensity, duration and quantity of rainfall events. Based on the 8-year analysis period, only precipitation exceeding 2–4 mm day^{-1} produced overland and interflow. Moreover, interflow was highest under very wet (snow-melt conditions) as well as very dry pre-storm conditions. Between these two extreme conditions, interflow was less pronounced, and is attributed to a predominance of gravity in respect to tension of dry surfaces, both of which favor bypass-flow.

Bypass and interflow seem to be strongly associated with human, animal and plant activities in the effective root zone. Consequently, hydrographic analysis demonstrated that the inverse value of the dry weather recession factor for direct runoff, representing the mean residence time in areas without groundwater-outflow, was shorter in the vegetation period (30 days) than during the winter season (60 days).

As compared to crops, mean residence times of interflow was found to be lowest in grasslands, intermediate in arable lands and highest in forest areas. In all the abovementioned areas, seasonal variations were observed.

4. Conclusions

Flow in the unsaturated zone is often so inhomogeneous that sampling at fixed points provides more reliable results for scaling up in a catchment than sampling by coring and extracting water from soil samples or unsaturated sediments. Only mass transport studies contribute to distinguishing between different forms of seepage flow, namely, bypass and matrix-flow; classical hydraulic observations in the unsaturated zone rarely allow such differentiations. Bypass-flow velocities are in the same order of magnitude as overland-flow and, in hilly terrains, turn into lateral or interflow at hydraulic interfaces paralleling morphology.

Interflow and overland-flow reduce groundwater recharge. Agricultural activities in hilly terrains predominantly influence infiltration and overland-flow. Conversely, groundwater recharge is mainly influenced by geologic structure and texture properties of the sediments (Behrens et al., 1980). Changing agricultural activities, therefore, impact predominantly the contribution of discharge to overland and interflow and, to a lesser extent, the contribution of groundwater recharge. Only changes from crop to grassland will affect groundwater recharge on the long run.

Since matrix-flow is an inadequate indicator to describe and land use changes on groundwater quality, the analysis of export processes in the effective root zone (Seiler and Hellmaier, in press) or in the direct runoff, provide fast information on both small and large scales of a catchment.

Acknowledgements

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