Study of runoff generation on hillslopes using tracer experiments and a physically based numerical hillslope model

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Abstract Artificial rainfall and tracer experiments were conducted on two hillslope sites to identify runoff processes and to test a double porosity physically based numerical hillslope model (QSOIL). The results show good agreement between the measured and the predicted runoff components, matric potential and water content. The spatial and temporal behaviour of the different runoff generation processes was determined. A distinct vertical macropore system, resulting in bypass flow, and as the major contributing region for surface flow a highly permeable structured A horizon were attributed to one hillslope site. In contrast, the soil of the other site showed a bimodal pore size distribution, assumed to be a combination of mesopores and micropores developed by plant roots, and resulting in a higher subsurface flow response.

INTRODUCTION

In the last 30 years, different approaches have been developed to describe runoff generation on hillslopes. Generally, runoff processes were observed by various field measurement techniques. Assuming a specific runoff controlling mechanism, rainfall-runoff models were developed for distinct time and space scales. However, a universally understanding of runoff processes was neglected, because rainfall-runoff models usually simplified the runoff generation. A process-orientated, physically-based model, however, is able to distinguish between different runoff processes, only if all flow processes are described and associated model parameters are measured.

The study of runoff generation occurring on 18 different hillslopes based on artificial extreme rainfall (Scherrer, 1997) provided insight into runoff processes. The mechanisms controlling runoff could not always be distinguished, although a physically based numerical hillslope model was used to predict discharge and soil moisture tension (Faeh, 1997). This model, QSOIL, can distinguish the following flow processes: surface flow, return flow, matrix flow, macropore flow and pipe flow. For this study, macropore flow is defined as water movement under small capillary forces vertically, while pipe flow is water movement laterally downslope. However, there are problems in estimating of model parameters. The objective of the present study, therefore, is to identify runoff generation processes on hillslopes by deriving the model parameters using all available information from field and tracer experiments, so that the usual parameter calibration is avoided.

METHODS

Field experiments

Two sites in the prealpine Swiss research basin Vogelbach were chosen for the experimental work. The plots 60 m^2 each, were located on 17-25° steep hillslopes. The hillslope are gleysols which developed from Sardonna-Flysch and are influenced by the different vegetation covers, i.e. forest and grassland. A detailed description of the soils is given in Table 1. Two extreme rainfall events of 60 and 100 mm h^{-1} were artificially simulated at each of the two hillslope research sites. In addition to the surface and subsurface runoff at the base of the plot and the subsurface pressure heads, water level and water contents were measured and simultaneous tracer experiments were performed. Soil water changes were monitored during the experiments with soil moisture probes (TDR), tensiometers and piezometers. A side view of the forest site with the measurement devices is shown in Fig. 1. Tracer experiments with bromide (NaBr) at the grassland site and fluorescein (Uranin) at both sites were conducted using different application and sampling techniques. As an example the flow, piezometer and tensiometer measurements taken during the second experiment at the forest site are shown (Fig. 2). The tensiometer response differed markedly and were affected by heterogeneities in hydraulic conductivities. No bypass flow, however, was detected. The breakthrough curves of fluorescein in the forest and grassland plots (Fig. 3) are similar to those expected for structured soils with different pore size distributions.

Table 1 Properties of the experimental sites: S = sand content, C = clay content, P = porosity. Grassland has grass harvested for hay.

Properties		**Location**	
		grassland	**forest**
Parent material		Sardona-Flysch	
Soil classification		Gleysol on Slopes	
Texture	A horizon	S: 43%, C: 14%, P: 65%	S: 21%, C: 38%, P: 57%
	B horizon	S: 27%, C:28%, P: 52%	S: 15%, C: 40%, P: 53%
	C horizon	S: 32%, C: 30%, P: 52%	S: 23%, C: 38%, P: 44%
Soil development		development of highly porous, well structured A-Horizon	weak development of horizon
Humus		mull	mould
Content of coarse fragments		10-15%	15-25%
Size of coarse fragments		< 40 cm (Cherty and cobbly)	10-100 cm (Stony)
Macropores		earthworm holes, mouse-holes	root channels
Slope		23°	17-25°

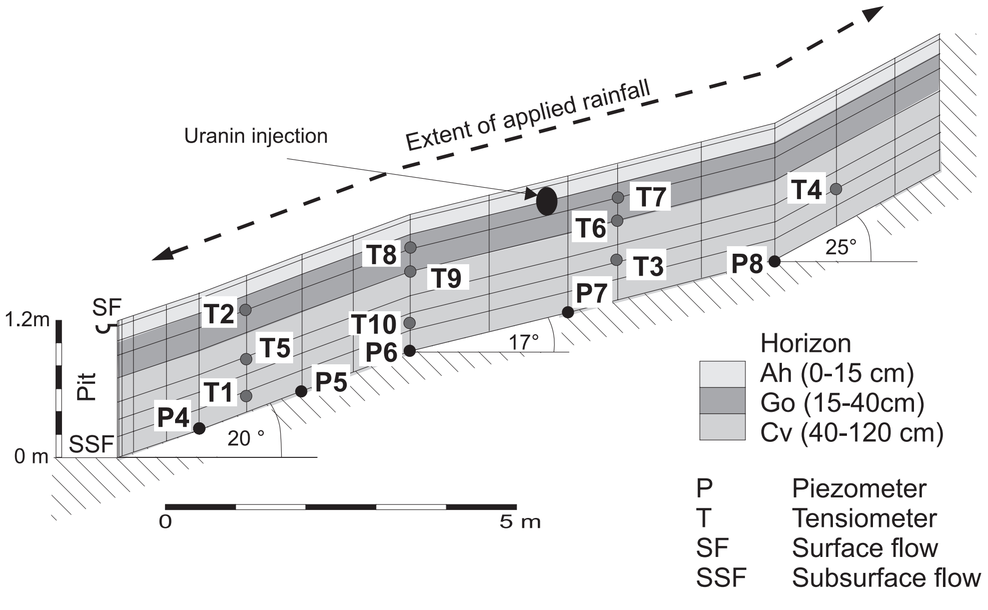

Figure 1 Side view of the forest site with the measurement devices, point of Uranin injection and discrete structure of the numerical hillslope model.

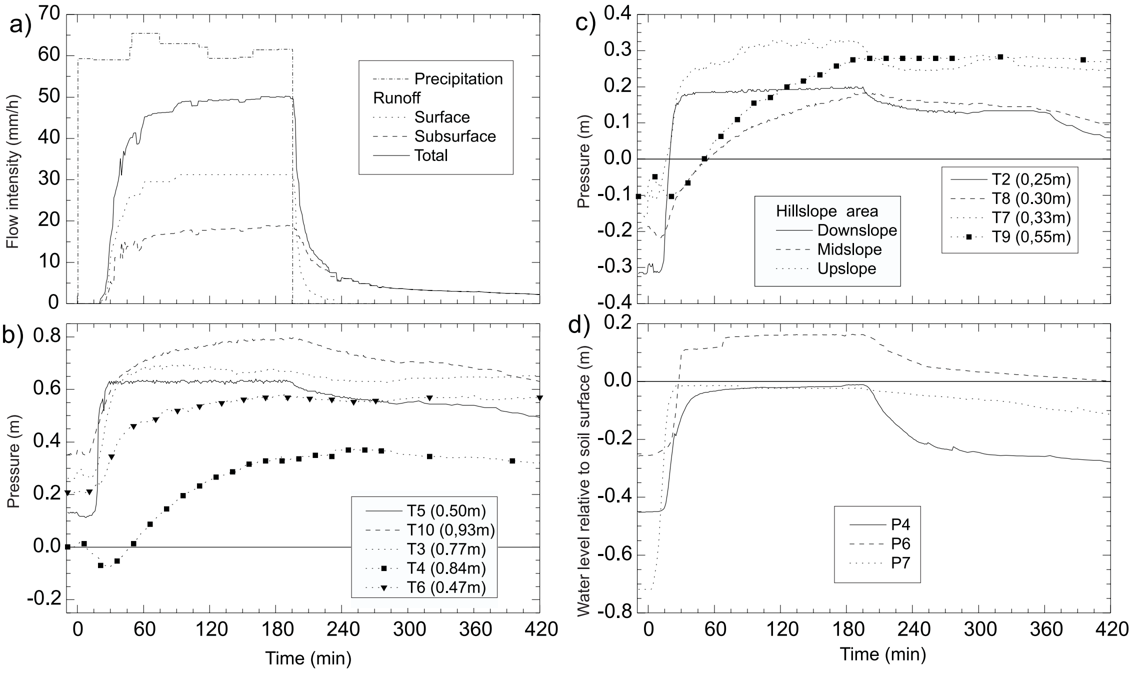

Figure 2 Flow (a), tensiometer (b, c) and piezometer (d) measurements during the tracer experiment at the forest site (for the location of the measurement devices see Fig. 1).

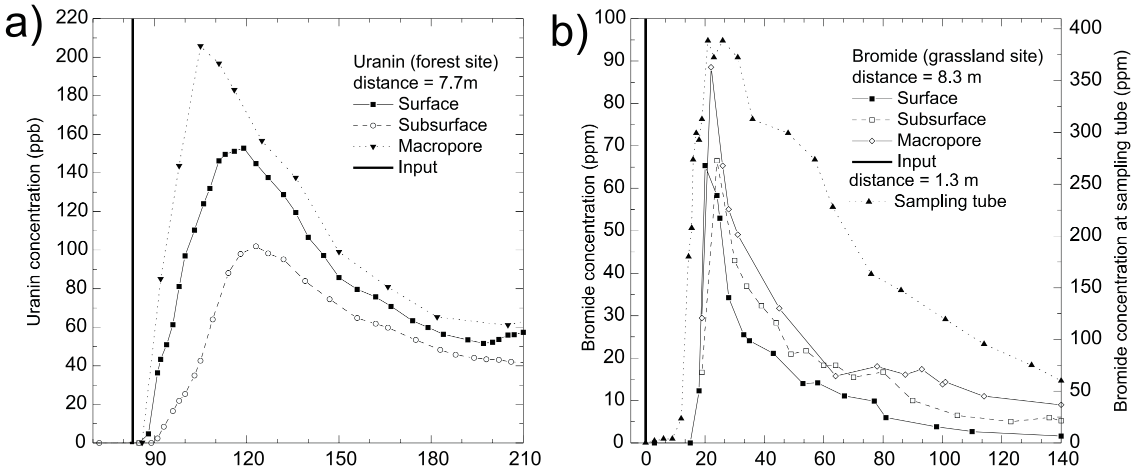

Figure 3 Breakthrough curves of Uranin during the second experiment at the forest site (a) and bromide during the second experiment at the grassland site (b).

Physically based numerical hillslope model (QSOIL)

A double porosity approach which links two domains, is used in QSOIL to describe flow in structured soils (Zuidema, 1985) because macropore flow generally has important effects on subsurface hydrology (Nielsen *et al.*, 1986). The first domain consists of the soil matrix, in which flow is described by the Richards equation. The equations are solved for two dimensions by means of the Galerkin-type finite element technique. Dirichlet and Neumann boundary conditions are accounted for, enabling various seepage faces to be modelled. The second domain consists of macropores in which average flow properties (macro-porosity and flow velocity in macropores) are used to describe the system through a one-dimensional vertical diffusion wave process. The exchange of water between the two domains is computed by an interaction module. The water exchange depends on the hydraulic potential difference between the matrix and macropore domains. The hydraulic potential difference is derived from the macropore diameter and the hydraulic conductivity of the macropore lining and the surrounding matrix material. The global parameter describing the interaction and the macropore flow, however, cannot be estimated from general behaviour. The tracer experiments were used indirectly for the assessment. Overland and pipe flow are computed as one dimensional downslope kinematic or diffusion wave processes. The use of the two dimensional QSOIL model is based on the assumption that little lateral water flows. The process elements that can be modelled are shown together with the parameters used by QSOIL in Fig. 4. For detailed information on QSOIL, see Faeh (1997).

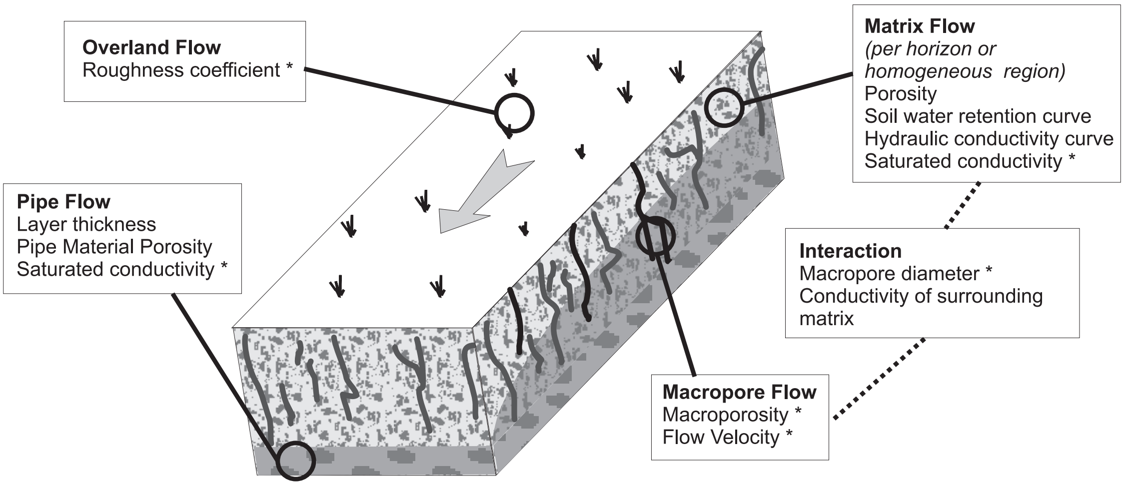

Figure 4 Flow process elements of the QSOIL model with their respective modelling parameters. The parameters marked with * are indirectly determined using the information of the tracer experiments.

Analysis of the tracer experiments

Different solute transport models were used in this study. In addition to the linear models, Convection-Dispersion-Model (CDM) and Transfer-Function-Model (TFM)

(Jury, 1982), the non-equilibrium models, Single-Fissure-Dispersion-Model (SFDM) (Maloszewski, 1994) and Mobile-Immobile-Water-Model (MIM) (Van Genuchten & Wierenga, 1976), were fit to the tracer breakthrough curves obtained from surface and subsurface runoff components, sampling tubes and single macropores in the pit. One model was selected for each breakthrough curve based on goodness-of-fit and the physical plausibility of the transport parameter. The agreement between predicted and measured tracer concentration of some breakthrough curves are shown in Fig. 5.

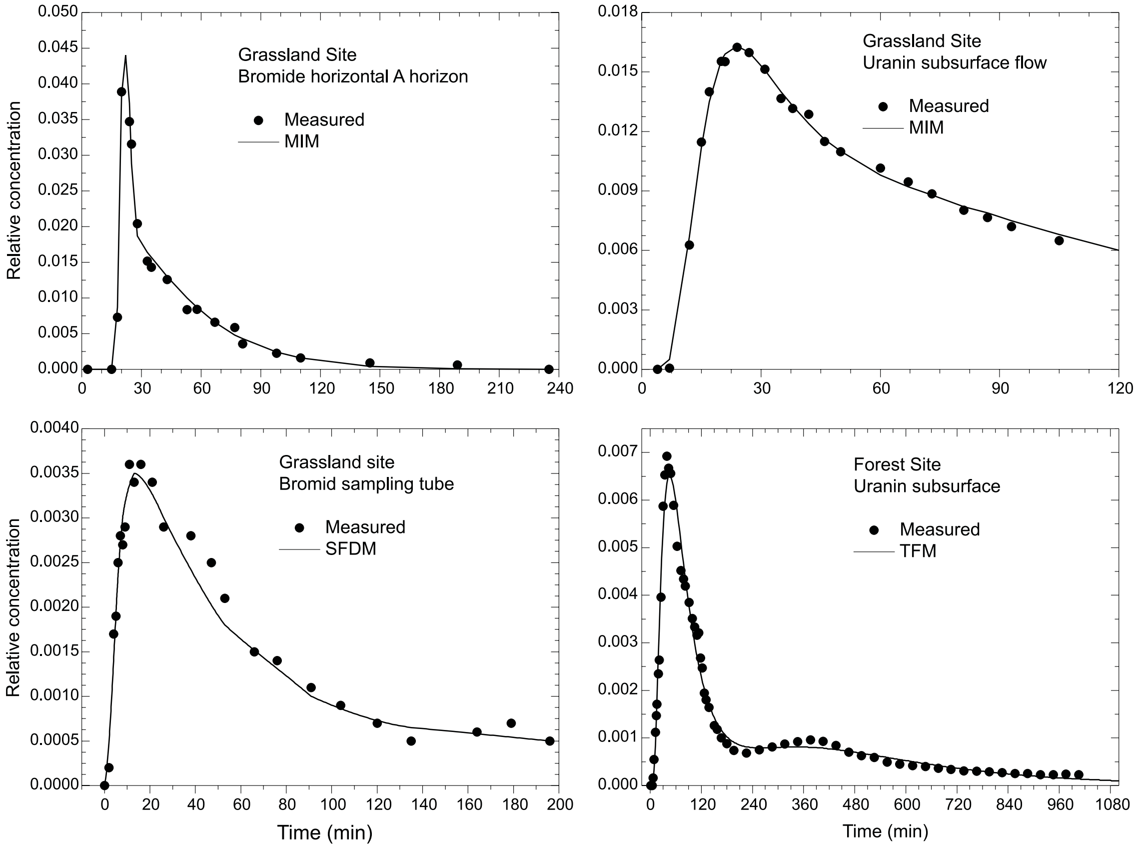

Figure 5 Examples of measured and fitted breakthrough curves for the forest site, using TFM, and the grassland site, using MIM and SFDM.

Parameter Determination

The distributed model QSOIL requires information for homogeneous regions of the hillslope. To define homogeneous matrix flow elements, the soil properties are used as horizon-specific parameters. These are determined through pedo-transfer functions (Rawls & Brakensiek, 1989) that define the soil water retention curve and the relative hydraulic conductivity curve. To use QSOIL the previously derived parameters of the transport models and other field experiment results (water balance and bail tests) were synthesized for determination of indirectly measurable flow parameters required by QSOIL. The flow parameters include saturated conductivity for each horizon, which was determined from the effective porosity and pore water velocity and combined with the results of the bail tests and calculations using Darcy's law. The global macropore parameters were determined from the mobile pore water velocity, the effective porosity and the calculation of the macropore diameter using the Manning's equation. This determination was a complex process because it considered all available information from the experiments and laboratory analyses. Nevertheless, the observed heterogeneity of the macropore flow at the hillslope scale makes it difficult to set one global parameter in QSOIL. The QSOIL parameters at both sites are listed in Table 2 .

Table 2 QSOIL flow parameters determined by analysing the results of rainfall and tracer experiments and soil properties. * horizontal values in A-Horizon at grassland site.

Location	**Saturated conductivities (m s^{-1})**			**global macropore parameters**			**overland flow**
	vertical per horizon *horizontal per horizon* **A horizon**	**B horizon**	**C horizon**	**flow velocity (m s^{-1})**	effective porosity (%)	**diameter (mm)**	roughness coefficient ($m^{1/3}$ s^{-1})
Grassland	2×10^{-5}	3×10^{-6}	3×10^{-6}	0.006	0.6	0.5	4
	1.7×10^{-3}	*5×10^{-5}*	*2×10^{-5}*	*0.04**	*10.0**	*3.0**	
Forest	1×10^{-5}	1×10^{-5}	4.4×10^{-7}	0.0015	4	0.07	1
	8×10^{-5}	*5×10^{-5}*	*4.4×10^{-7}*				

RESULTS AND DISCUSSION

The computations with the QSOIL parameter values were derived from field and laboratory data and not from calibration with both the discharge and pressure change measurements. The simulations of each site reveal important differences in their runoff processes.

Grassland site

The transport parameters (Table 2) for the grassland site show realistic values for the macropore domain and are consistent with field observations of earthworm holes, the major origin of vertical macropores, and mouse-holes, the major origin of horizontal macropores. The simulation results describe the measured matric potential well. The calculated surface and subsurface flow components match the measured data especially well. Field observations already suggested the importance of the upper soil horizon (A horizon) as the major contributing region to the measured surface flow. Actually, 70% of the simulated surface and near surface flow originates from this horizon. Runoff generation was mainly controlled by the highly permeable A horizon and the strongly developed vertical macropore system in deeper horizons, which results in bypass flow.

Forest site

The infiltration process and the development of the macropore structure of the forest site differs from the grassland site. The high effective porosity (4 %) and the low effective pore diameter (70 :m) of forest site macropore system differs significantly from those of the grassland site (Table 2). The pore system is develped by plant roots, which form a dense lateral and vertical net of pore-channels, having mainly small diameters. The analysis of the breakthrough curves supports this hypothesis because of the high diffusion of the tracer from the mobile to the immobile phase. The high diffusion implies a pore domain with a small pore diameter and thus strong capillary forces and no hydraulic separation between the two pore domains. Additionally, there was no bypass flow observed at this site. Consequently, the soil at the forest site can be described by a bimodal pore size distribution, assumed to be a combination of mesopores and micropores (Wilson *et al.*, 1990). The results of the QSOIL simulations using these assumptions are shown in Fig. 6. The different respones of the tensiometers and piezometers are well simulated, but the surface flow, however, is overestimated, probably due to lateral losses after the soil is saturated. Consequently, a relation for the selection of the suitable transport and flow models for different flow paths could be developed (Table 3).

Table 3 Observed relation of the experimental site and flow paths to the suitable transport and flow models for different pore size distributions.

Experimental site *Flow path*	Pore size distribution	Transport model	QSOIL
Grassland *Subsurface flow in Go/C horizon*	Unimodal	CDM	Matrix flow
Forest *Infiltration and subsurface flow*	Bimodal	TFM	Matrix flow with properties for a bimodal pore size distribution
Grassland *Infiltration and subsurface flow in A-Horizon*	Matrix and well developed macropore system	SFDM MIM	Matrix flow macropore flow (pipe flow)

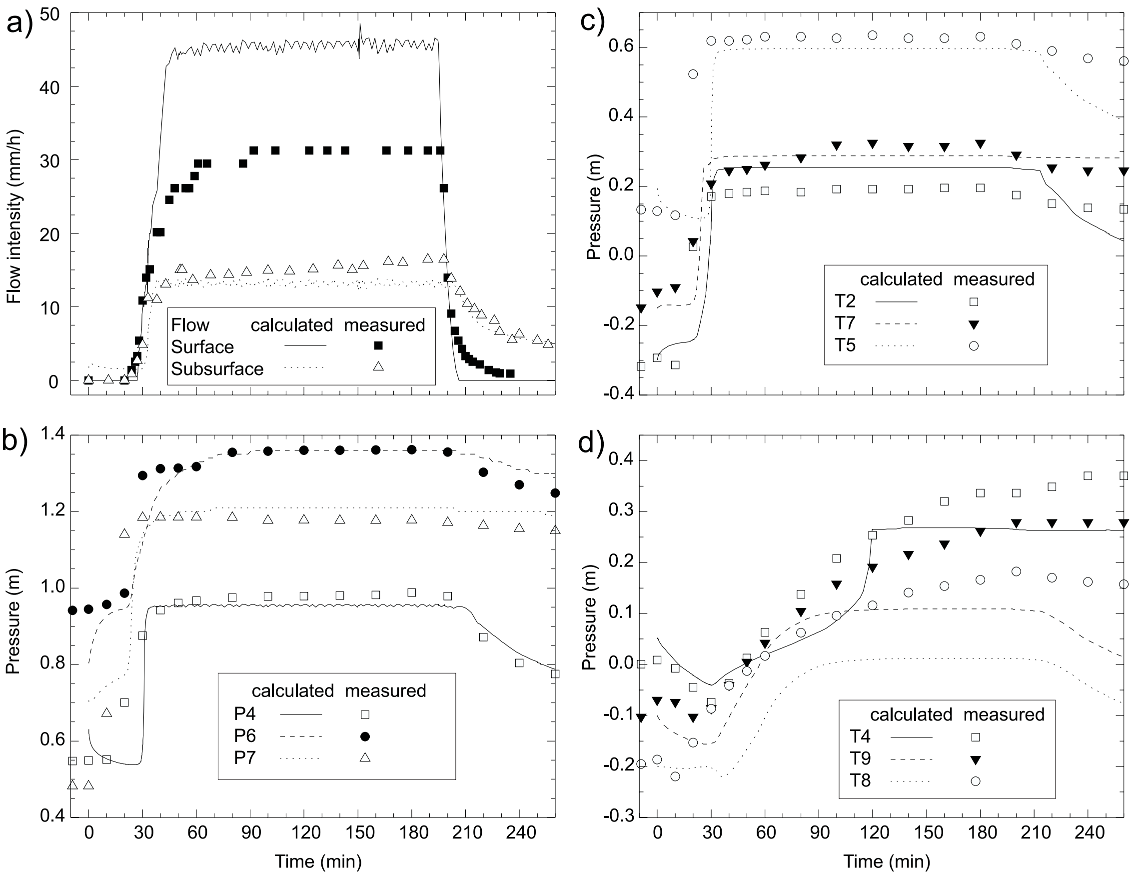

Figure 6 Simulation results for the forest site using a bimodal pore size distribution (for the location of the measurement devices see Fig. 1).

CONCLUSION

On the condition that measurements and simulations of runoff processes are conducted in the same spatial and temporal resolution, the combination of artificial rainfall and tracer experiments provides a suitable tool for identifying and characterizing discharge formation processes. This method also supplies information to determine difficult to measure parameters for QSOIL. There are, however, limits to the extent to which distinct microscale components and processes can be described. The hillslope-scale does not seem suitable for the identification of a single microscale process, because the simulations are based on so-called "effective parameters" derived from tracer experiments. The transformation of transport parameters into flow parameters is critical if the structure of the fitted solute transport model does not account for real physical flow mechanisms. To minimize these difficulties, future research should focus on developing transport and flow models that are linked to each other. Furthermore, there is a need for the physical flow descriptions of the matrix and macropore flow to be validated at different scales.

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