Hydrology and Earth System Sciences, 4, *787–800* (1997) © EGS

Hydrology & Earth System Sciences

A combined field and numerical approach to investigate flow processes in natural macroporous soils under extreme precipitation

Andrew O. Faeh*, Simon Scherrer and Felix Naef

* Presently at: HEIERLI Consutling Engineers, Culmannstrasse 56, CH-8033 Zurich. Tel (+41) 1360 3123, Fax (+41) 1360 3100, E-mail: faeh@iname.com
Institute for Hydromechanics and Water Resources Management (IHW), Swiss Federal Institute of Technology, ETH Hoenggerberg, CH-8093, Zurich

Abstract

A procedure involving simultaneous experimental and numerical research is described for the purposes of understanding the mechanisms involved when extreme precipitation is transformed to flood stream discharge. It is shown that experiments and model applications by themselves are not sufficient for process identification, but that their combined application provides considerable insight into the subsurface flow processes. The proposed approach is unconventional in that a numerical model, based on stringent continuity and momentum criteria, is used as a tool for process identification only. Unlike other studies, it is not intended to demonstrate the applicability of the utilised model for general hydrological applications, or to provide evidence of the suitability of particular model simplifications. Rather, different and sometimes conflicting model realisations are used to examine the plausibility of flow processes which may occur on natural hill slopes. Hereby, small scale effects such as those relating to the mechanisms of water entry into the macropores, and the movement of water to the surrounding matrix are identified from the results of well instrumented field experiments.

Introduction

The flood forming transformation of precipitation into stream discharge during intense storms represents the resultant response of the flow processes generated in and on natural soils. The features of these transformation mechanisms, referred to as 'discharge formation' in this paper, are however still not fully understood.

Current discussions on climate change and recent devastating flood events have globally heightened public and scientific interest on the origins and magnitudes of floods. This interest lead to a project aimed at undestanding the relationship between catchment retention and the magnitudes of floods. Within this project more insight was sought into the processes governing discharge formation during intense storm events. Using this newly won information, more accurate assessments of catchment retention can now be made, thereby enabling the reliability of flood predictions to be improved.

This paper reports on and demonstrates the combined experimental and numerical methodology which was developed and applied to obtain insight into the flow processes occurring in and on natural macroporous soils at the hillslope scale. Various authors have identified the need for such simultaneous experimental and numerical investigations for progress to be made in the understanding of the hydrological processes (*Dunne [1983]*, *DeCoursey [1991]*, *Binley et al. [1991]* and *Abbaspour and Schulin [1996]*). In fact, *Grayson et al. [1992]* state that the link with reality is often lost when numerical techniques are employed in the absence of congruent experimental measurements. A long recognised but little applied hydrological investigational approach is thus presented here for extreme precipitation conditions.

A brief description of the current theory on the paths and processes involved in soil water movement, and the process definitions upon which this study is based, is firstly given. Following separate descriptions of the field and numerical techniques adopted, the methodology employed in the study is described for one of the sites examined. Finally, efficacy of this approach is shown by presenting the factors which were thereby identified to control soil water movement at this site.

SOIL WATER FLOW MECHANISMS

Differentiation between the characteristics of soil water movement is commonly made on the basis of the dimensions and connectivity of the soil pore spaces in which water transportation occurs. Water movement in soils is thereby described as a combination of matrix flow, where water passes though the pore-spaces between individual soil particles, and the mostly rapid bypass flow, which is characterised by water movement in structural soil features.

Matrix flow, which occurs under both saturated and unsaturated conditions, is diffuse in nature and is often unstable, i.e. instead of advancing as a smooth front, water may concentrate at certain locations and advance (usually vertically) in the form of finger-like or tongue-like protrusions (*Hillel [1987]*). This phenomenon which is referred to as 'wetting front instability' or 'fingered flow', has however been found to be less significant than bypass flow for high rainfall intensities such as those of this investigation (*Steenhuis and Parlange [1991]*).

BYPASS FLOW SYSTEMS

When water enters a structural feature in the soil, such as a crack or a worm hole, it is no longer subjected to capillary forces as in the matrix, and movement which is more rapid than matrix flow can occur. This rapid water movement is termed 'bypass flow' because the soil matrix is short-circuited by these flow channels. The term 'preferential flow' is sometimes also used to describe such flow. As no commonly accepted definition of these terms exists, it is proposed here that the use of the term 'bypass flow' be restricted to water movement in structural soil features such as macropores and pipes. Preferential flow could then be understood as a global term encompassing both the bypass flow processes and non-uniform matrix flow due to wetting front instabilities.

The characteristics of bypass flow are substantially different to those of matrix flow, i.e. a large portion of flow occurs in a small percentage of the total soil pore volume. Within the soil body, non-uniform flow fields with widely different flow velocities are obtained under bypass flow conditions. *Gerke and van Genuchten [1993]* note that pressure heads of these flows are discontinuous and that this severely complicates the prediction of flow processes in natural soils.

Bypass flow, as referred to in the literature (*Bouma [1981]*, *Beven and Germann [1982]*, *White [1985]*, *Nielsen et al. [1986]* and *Hornberger et al. [1990]*), is typically described to occur in macropores and pipes. However, no clear distinction between these two features exists. In this paper they are differentiated on the basis of their lengths and orientation, which differ according to the factors resulting in their formation, and not with regard to their cross sectional size, as their names might imply. Predominantly vertically orientated flow channels, with lengths comparable to those of the soil depths or horizon thicknesses, are considered to be macropores here. Slope parallel channels which are sufficient in length to influence the flow processes at the hillslope scale are referred to as pipes. The effects of macropores are most pronounced on infiltration, whereas pipes mainly influence subsurface hillslope drainage.

MACROPORE PROPERTIES

Differentiation can be made between two main types of macropores, i.e. cylindrical holes and planar cracks. Holes arise either due to biological (e.g. worm or ant) activity or as passages left by root decay. Cracks open under dry soil conditions but close on rewetting. Holes, however, generally display less variability. The vertical, permanent burrows of surface feeding earthworms, for example, are stabilised by smooth linings made up of earthworm mucus secretions with high clay and silt contents (*Banse and Graff [1968]*). Either bark material, which is more resistant to decomposition, or translocated clay and oxides can coat the surfaces of holes formed by root decay (*Schoeneberger and Amoozegar [1990]*). Due to their variability, crack linings are often less pronounced than those of holes. Linings are usually absent for newly formed cracks.

Very little is known about the physical and chemical properties of hole linings which often serve as the interface between the macropore and the matrix systems. The available studies suggest that hydraulic conductivity of the interface can be much less than that of the matrix interior (*Gunzelmann [1990]*, *Thoma et al. [1992]*), and that in some cases water transfer between the macropores and the matrix can be virtually eliminated by hole coatings.

INFILTRATION

Infiltration is commonly analysed as a purely vertical matrix flow process originating at the soil surface (e.g. *Philip [1991]*, *Protopapas and Bras [1991]*, *Weir and Kissling [1992]* and *Smith et al. [1993]*). The infiltration potential of soils is thereby believed to be controlled chiefly by the properties of the soil surface (*Römkens et al. [1990]*, *Bouma [1992]*, *Burch et al. [1989]*, *Dixon and Simanton [1977]*). However, water entry into natural macroporous soils is not a one-dimensional process, as infiltration occurs not only at the soil surface but also in a distributed fashion throughout the soil body through the walls and bases of the macropores.

The various components of infiltration defined in this study are shown in Fig. 1. 'Matrix infiltration' refers to the classic wetting front type infiltration which originates at the soil surface and is affected solely by matrix flow. The term 'macropore infiltration' applies to the mechanisms by which water enters the macropores; be that at the soil surface or within the soil body itself. Contrary to the suggestions of *Dixon and Simanton [1977]* and *Bouma [1992]*, water entry into the macropores is assumed not to occur at the soil surface only, but also within the soil body. The movement of water from the macropores into the surrounding matrix is defined as 'interaction infiltration'. The total infiltration which can occur via the macropore system depends therefore on both the macropore and interaction infiltration characteristics.

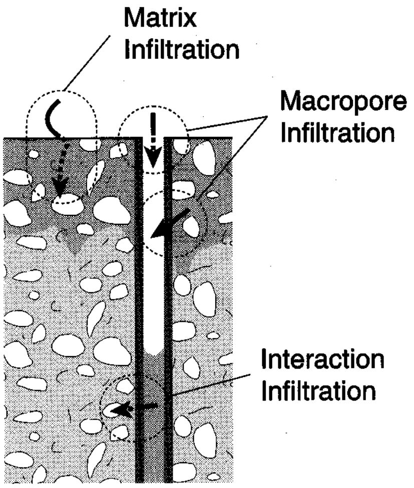


Fig. 1 *The various infiltration components taken into consideration in this study.*

Field Investigation

PURPOSE AND DESIGN

As this study was intended to understand the variability of discharge formation, a total of 48 experiments were performed at 18 different sites throughout Switzerland. The flow processes occurring in and on a wide range of soil types and hillslope characteristics were thereby examined. The investigation was restricted to sites not prone to soil erosion, and thus the experiments were performed mostly on cow pastures or other locations displaying good natural vegetation cover.

To ensure the success of an investigational approach involving concurrent field experimentation and numerical simulation, a strong interaction between these two techniques is essential. The experimental set-up and procedure for the field investigation was thus optimised such that it would provide the necessary information for the numerical techniques adopted.

EXPERIMENTAL SET-UP AND PROCEDURE

A rainfall simulator with which uniform, extreme precipitation of constant intensity could be simulated, was employed for the field studies. A wide range of scales for such rainfall simulation experiments are reported on in the literature, varying from less than 1 m^2 (*Naslas et al. [1994]*) to more than 1 ha (*Lynch et al. [1977]*). In this study conflicting requirements had to be satisfied in the choice of experimental scale. Rainfall application over a sufficiently large area was desired here to minimise the influence of isolated macro scale effects. However, portability of the experimental apparatus was essential in order to be able to perform comparable experiments at differing sites. In common with the findings of other researchers (e.g. *Lehnardt [1985]*), the plot scale (ca. 50 m^2) was deemed to be most suited to fulfil these differing criteria and satisfy the requirements of this study.

The experimental set-up is shown in Fig. 2. Rainfall was simulated over an area of 60 m^2 (4 m across slope and 15 m upslope). In keeping with the aim of the investigation, high rainfall rates of up to 100 mm/h were applied. To facilitate the comparison of the experimental results, it was attempted to utilise the same intensities at all sites. This was not always possible due to differences in pump supply pressures. Rainfall intensities thus varied between 50 and 110 mm h^{-1}.

Both the overland and the subsurface flows generated were monitored at the lower ends of the experimental plots. Less than half a metre downslope from the lower boundary of the plot, a trench was cut perpendicular to the slope direction. The trench was extended, where possible, down to an impervious layer, otherwise to a depth of about 1.2 m when no impervious layer or bedrock was found. An aluminium tray to collect the overland flow was driven into the trench face as close to the surface as possible (usually at a depth of about 5 cm). The overland flow was measured continuously, either by means of a tipping bucket or with the aid of a measuring weir depending on flow rate. Water from subsurface flow, which collected at the bottom of the trench, was also measured continuously as flow from the drainage pit. Plastic covers, usually placed on both sides of the experimental plot, served as *plot delineation. Water flows off these covers were measured and subsequently deducted from the supply flow rates.*

Instrumentation was selected and installed with the aim of being able to identify the soil water flow processes responsible for the observed discharge formation. Unsaturated subsurface flow processes were monitored by measuring soil moisture contents with TDR probes (time domain reflectrometry), and tensiometers measuring soil suctions. Piezometers were employed to indicate the extent of soil saturation. Some piezometers were installed outside the plot in order to monitor sideward water flows away from the plot. Precise details regarding the instruments and apparatus employed can be found in *Scherrer [1996]*.

Sites with largely two dimensional flow processes were examined. To maximise the downslope flow and reduce the loss effects of sideward and deep percolation flows, experiments were conducted on relatively steep hillslopes, with gradients between 13% and 55%. Only slopes displaying little transverse gradient were considered, and slopes suggesting convergent or divergent flows were generally avoided.

Wherever possible, rainfall was applied until a steady state in the resulting flows was attained, and maintained for approximately one hour thereafter. This meant that

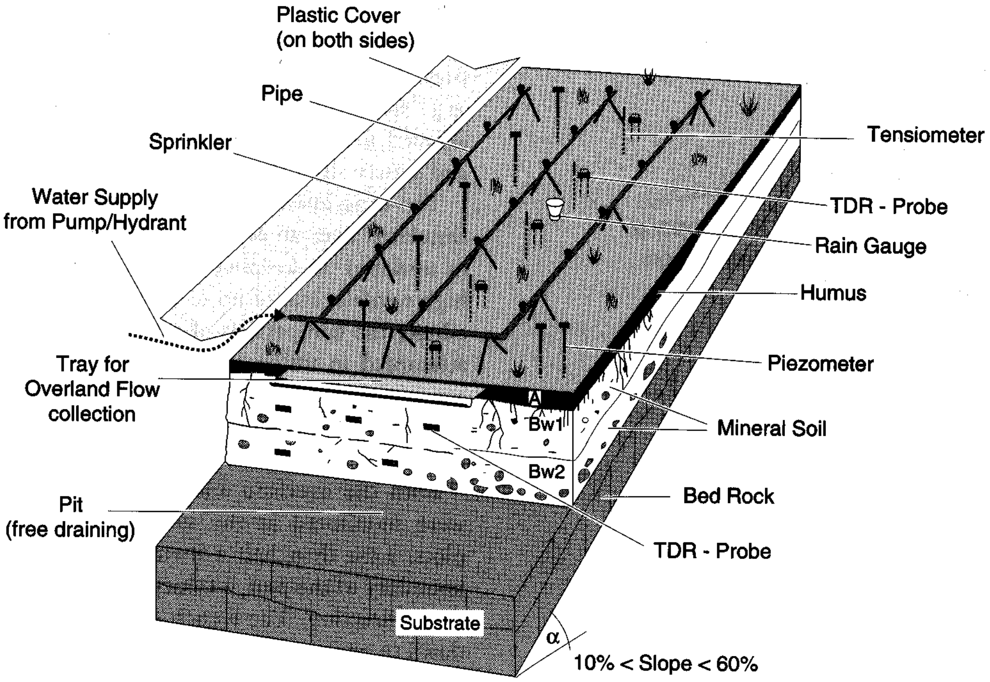


Fig. 2 *Experimental set-up of the rainfall simulation experiments, conducted on 60 m2 plots (4 m × 15 m). Not shown is a wind-break fence, which was mounted (when required) adjacent to the plastic covers. Water was supplied either by pumping from nearby streams or preferably from fire hydrants.*

rainfall was mostly simulated for periods of between two to six hours.

It was attempted to obtain direct field conductivity measurements for the different horizons of the soils examined. Unfortunately the Guelph Permeameter (*Reynolds and Elrick [1986]*) employed was found to be highly susceptible to smearing effects and therefore generally provided unreliable values. As an alternative, an analysis of Pedotransfer functions such as those proposed by *Rawls and Brakensiek [1985]* indicated their suitability for deriving the hydraulic properties of the Swiss soils examined (*Faeh [1997]*). Using the soil texture measurements (particle fractions, porosity) taken for the various soil horizons, the saturated and unsaturated hydraulic properties were thereby determined for the various sites examined. These values, and general site characteristics observed, provided useful information which aided the analysis of the experimental observations.

VISUAL FLOW IDENTIFICATION

Complementary to the instrument measurements, the various flows and their origins were also visually monitored during the experiments. Overland flow, for example, could be seen to originate from different sources. In some cases overland flow was observed to be sheet-flow, i.e. the entire soil surface was covered with a thin and relatively uniform film of water. Overland flow was however, more frequently observed to flow into the collecting trays in separate flow concentrations, these being dictated by the microtopography of the slope. Another curious, albeit infrequent, source of overland flow was return flow, i.e. the exiting of water from mouse holes immediately upslope of the collection trays. Unfortunately, the overland flow originating from return flow could not be measured differentially from that of the conventional overland flow. Return flow quantities could thus, at best, only be approximated.

Subsurface flow was, in most cases, observed to exit in a diffuse fashion from the soil profile. Water emitting from preferential pathways or macropores could not easily be distinguished. In most instances, flow simply appeared to be more concentrated at isolated locations, without macropores being identifiable to the naked eye. Well developed macropore flow, where jets of water flowed under pressure out of isolated macropores, was however sometimes observed.

CHARACTERISTICS OF A TYPICAL EXPERIMENTAL SITE, WILLERZELL MULDE

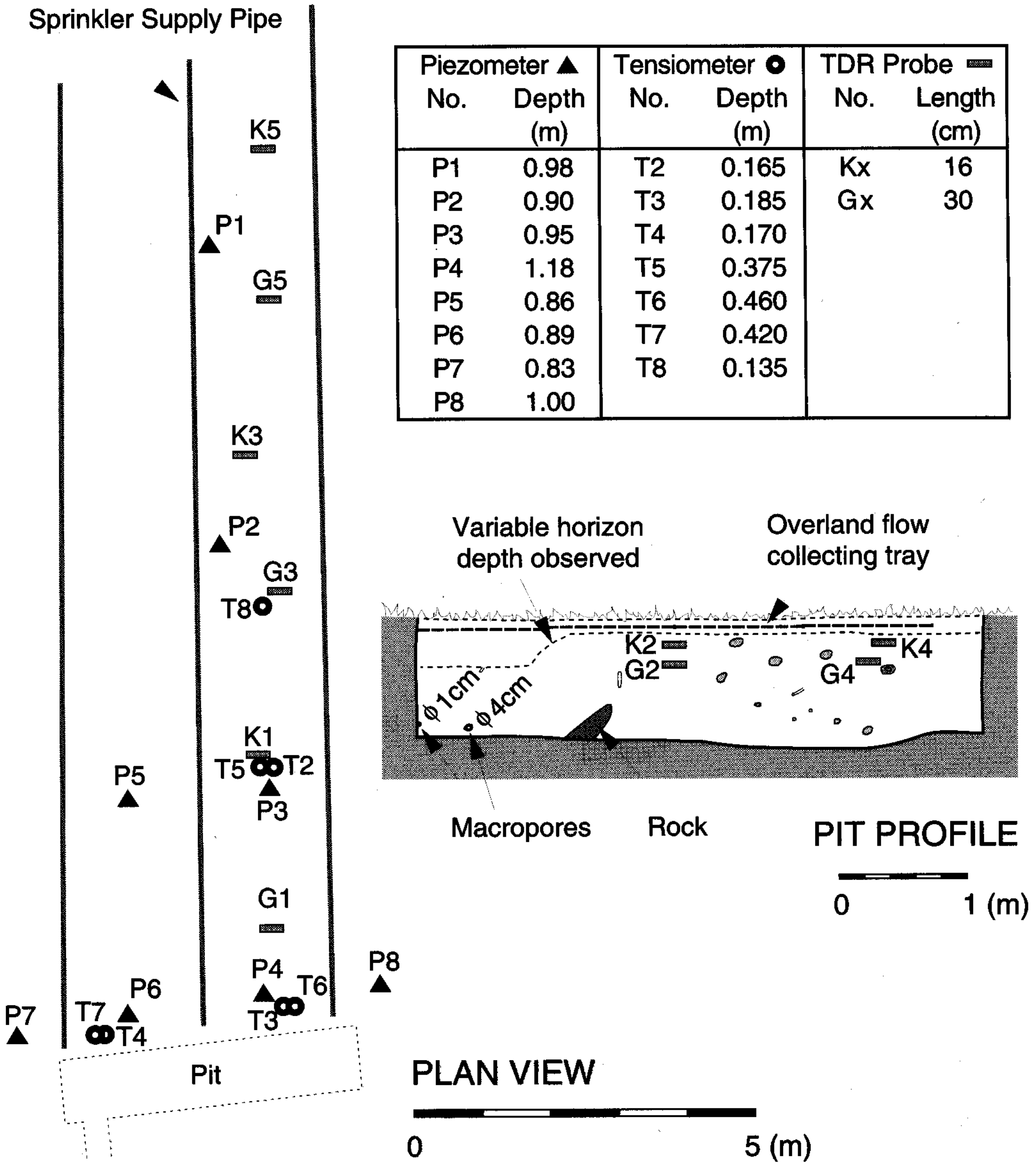
The flow process identification procedure described in this paper, is demonstrated for the site Willerzell Mulde, being one of the eighteen plots investigated in Switzerland. A comprehensive analysis of the entire data set, and its implications on flood formation in general, is dealt with by *Scherrer et al. [in preparation]*.

The experiment described here was conducted near the village of Willerzell, which is situated in the Canton of

Schwyz (central Switzerland), approximately 15 km southeast of Zurich. As its German name implies, the experimental site Willerzell Mulde was located in a depression about 50 m upslope of a stream. Due to the narrowness of the depression, the experimental plot was slightly concave in its cross-section. Longitudinally the slope of the plot was variable, with a slope angle of 21° (39%) in the upper region, decreasing to 15° (26.5%) in the vicinity of the pit.

A very heterogeneous colluvial gleysol soil overlying a greyish sandstone of the subalpine freshwater Molasse was found in this depression. The soil depth, horizons and properties displayed considerable variability. The grading of the mainly sandy soil was very diverse, with silt and clay particles occurring in approximately equal proportions. Moraine deposits were evident in the form of pebbles and boulders. Bedrock level was uneven, occurring between 60 and 180 cm below the soil surface.

The soil profiles examined displayed grey hydromorphic zones at varying depths below the soil surface. The lack of a systematic pattern for the depth at which hydromorphic conditions were located could be attributed to the heterogeneous nature of the colluvial deposits, which lack clearly defined soil horizons. At the pit face, for example, the humus horizon (Ah) was almost 40 cm thick on the left hand side (left and right are defined looking upslope), whereas only a 20 cm humus layer was present on the right (see Fig. 3). The water-table elevation was similarly erratic, probably due to local differences of the colluvial



Piezometer ▲		Tensiometer ●		TDR Probe ▬	
No.	Depth (m)	No.	Depth (m)	No.	Length (cm)
P1	0.98	T2	0.165	Kx	16
P2	0.90	T3	0.185	Gx	30
P3	0.95	T4	0.170		
P4	1.18	T5	0.375		
P5	0.86	T6	0.460		
P6	0.89	T7	0.420		
P7	0.83	T8	0.135		
P8	1.00				

Fig. 3 *Layout of experimental set-up showing positioning of measuring instruments at Willerzell Mulde. TDR probes shown on the plan view were installed vertically whereas those in the pit were installed horizontally.*

material and its hydraulic conductivities. Rust stains which serve as indicators for bypass flow (*Germann [1981]*) were found over the entire soil depth. In the lower horizon (Gr), such stains were concentrated around root passages. Observed earthworm activity was low, and was found to be confined mainly to the humus horizon.

TYPICAL EXPERIMENTAL MEASUREMENTS

Although the instrument positions were not identical at all sites examined, similar instrument arrangements were employed. The exact layout of the instruments installed at the site Willerzell Mulde is shown in Fig. 3, and the measurements made for a typical experiment at this site are shown in Fig. 4. The TDR readings are not shown as their restricted penetration depths and close proximity to the trench face allowed little information on the flow processes within the soil body to be gleaned from these measurements. The measurements made at the other sites described in this paper, and a comprehensive analysis of these observations can be found in *Scherrer [1996]* and *Faeh [1997]*.

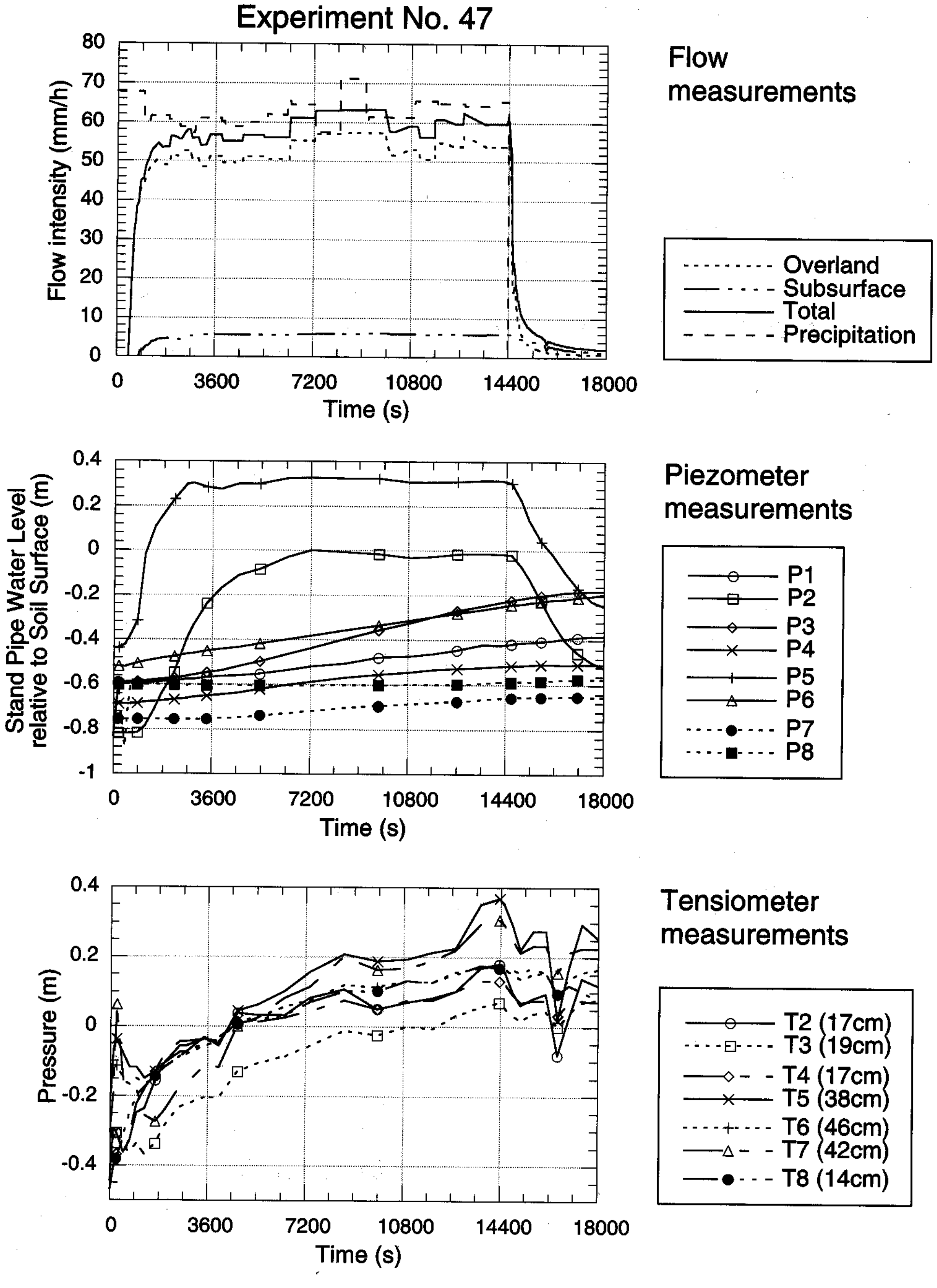


Fig. 4 *Flow, piezometer and tensiometer measurements made during Experiment 47 at Willerzell Mulde.*

In the experiment shown in Fig. 4, the soil water levels were between 0.4 and 0.8 m before rainfall application was started. After a delay of 7 minutes overland flow was initiated in response to the rainfall, simulated at a rate of around 70 mm/h. Thereafter a rapid increase in overland flow was recorded. Some subsurface flow, which emanated mostly from two pipes at the lower pit level was registered within 12 minutes of rainfall initiation. Stable, maximum flow rates were attained after 30 minutes. At this time, however, the piezometer and tensiometer values were still displaying continual change. The rapid water level increases recorded by the Piezometers P2 and P5 contrasted significantly from the remaining piezometer readings which continually and gradually rose for the entire duration of the experiment. The tensiometer values confirmed that the bulk of the soil body experienced gradually rising soil water levels. Bypass flow probably resulted in the short-circuiting of the rapidly responding piezometers. Whereas these two piezometers seemed to indicate the macropore system pressures, the remaining piezometers and all the tensiometers reflected the soil matrix pressures. Even after the cessation of rainfall application, some increase of the soil water levels was indicated by the slow responding piezometers. Complete soil saturation was not achieved during the experiment.

As shown in Fig. 5, a preliminary classification of the flow processes which occurred during this experiment could be made on the basis of the experimental measurements. The infiltration capacity was exceeded over widespread areas of the experimental plot, resulting in infiltration excess overland flow. In the isolated regions, where the soil water levels extended to the surface, saturated overland flow was generated. Bypass flow occurred in macropores, pipes and highly permeable lenses. The limited subsurface flow measured suggested however, that there was little connectivity between these systems. Martix flow was effective throughout the soil body and was responsible for the slow response of the majority of the instruments.

QUESTIONS POSED BY THE FIELD INVESTIGATION

Although the measurements provided a good insight into the flow processes which occurred at the various sites, certain aspects relating to the soil water movements could not be identified on the basis of the measurements alone. For example, at moist depression locations such as Willerzell Mulde, strong overland flow is generally associated with low infiltration arising from the attainment of widespread soil saturation. However, soil saturation was not indicated

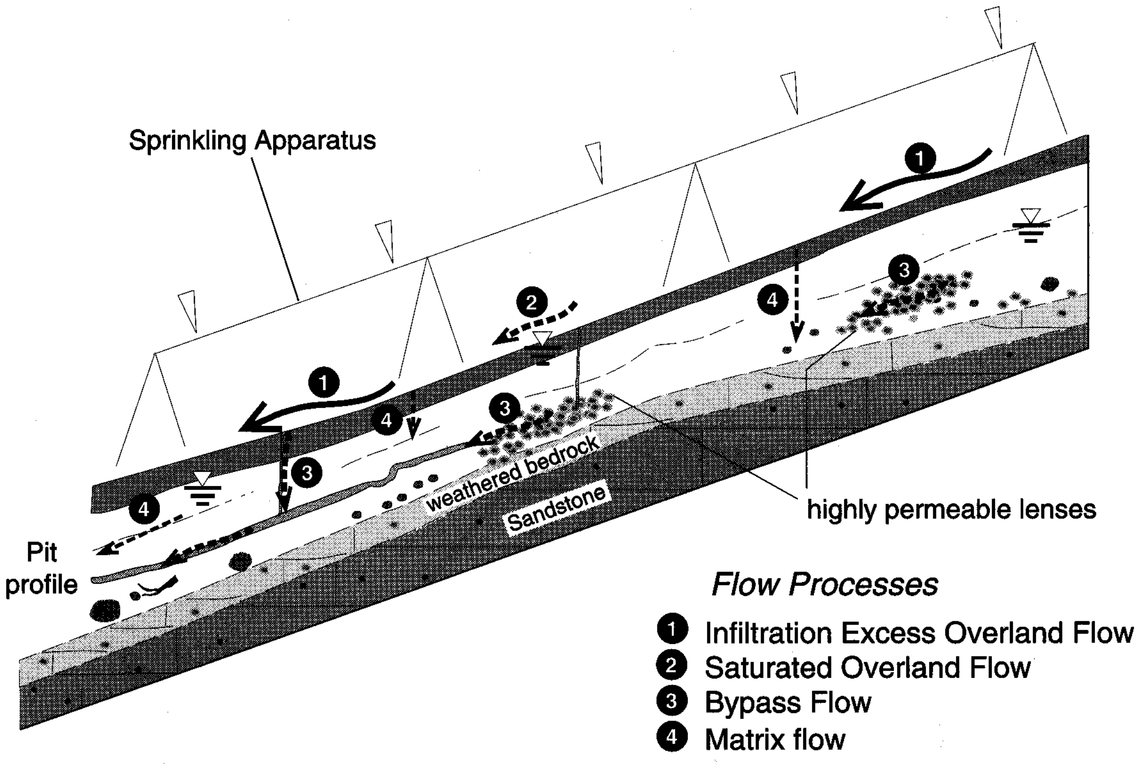


Fig. 5 *Preliminary identification of the flow processes at Willerzell Mulde based on the experimental observations and measurements only.*

during the experiments, and the rapid overland flow measured was thus apparently generated independently of the soil water content. Furthermore, infiltration seemed to be less than the matrix conductivities and the presence of bypass flow suggested. Discharge formation at this site was thus unclear because it was not possible to explain what caused the poor infiltration measured, nor where and how macropore flow was initiated, and what the relative proportions between matrix and macropore flow were.

Through the application of a numerical model, answers to these types of questions were sought, thereby enhancing the analysis of the experimental measurements.

Numerical Modelling

THE QSOIL MODEL

The QSOIL model employed in this investigation, represents a further development of the model conceived by *Zuidema [1985]*. In this physically based, two-dimensional model, described in detail by *Faeh et al. [in preparation]*, the equations of flow are solved by means of the Galerkin-type finite element technique. Both Dirichlet and Neumann boundary conditions are accounted for, enabling variable seepage faces to be modelled, such as those occurring at a pit wall.

QSOIL comprises of various modules describing different flow processes, these include overland, matrix, macropore and pipe flow. Overland flow is described numerically using the Kinematic wave approach, matrix flow with the Richards equation and macropore and pipe flow as Kinematic waves or Diffusion waves, depending on the state of filling in these structural soil features. An interaction module, defining the water exchange between the matrix and macropore systems also forms an integral component of the model. One-dimensional Richards equations, appropriately formulated for crack or hole type macropores, are generally solved to define the interaction flows. Because processes can be added or excluded as desired, the complexity of QSOIL simulations can vary considerably, from the simple case where only overland flow is modelled, to calculations involving simultaneous overland, matrix, macropore and pipe flow.

The process elements of QSOIL are shown in Fig. 6 together with the parameters upon which their modelling is based. Values for these parameters can mostly be obtained by field measurements, e.g. for matrix flow, or by adopting commonly accepted coefficients, e.g. surface roughness. Parameter estimation for the macropore and pipe flow systems is in the absence of direct measuring methods or generally recognised coefficients somewhat more intuitive. Macroporosity values were, for example, obtained here on the basis of soil crack spacing observations and/or worm hole counts. Worm holes were examined for the presence of linings, the conductivities for which were estimated as functions of the matrix conductivities.

Within the numerical model QSOIL, the system structure and the flow process sub-models define the soil system under investigation. The system structure sub-model describes the soil body geometrically, i.e. the hillslope

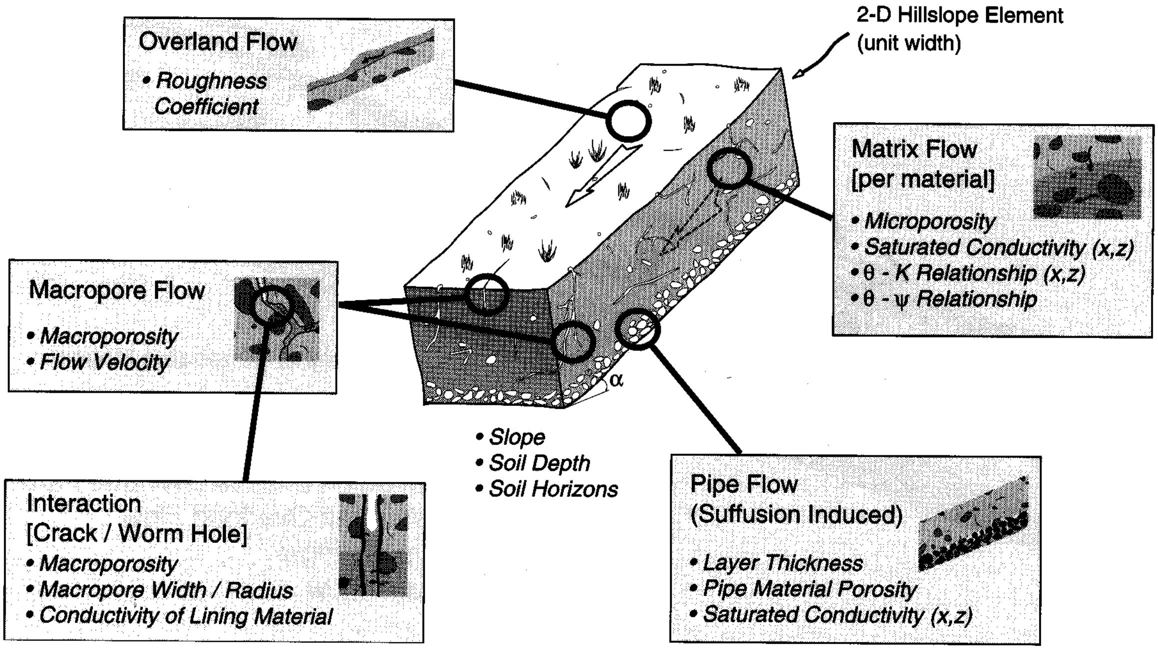


Fig. 6 *A schematic representation of the flow process components of the QSOIL model, the physical parameters required by the simulation model for each process are shown in italics.*

section under consideration, and the boundaries between the soil horizons contained therein. Discretization of the elements of the system structure sub-models is based on the available topographic information and visible soil properties, such as horizon thicknesses, and the accuracy requirements of the computations to be performed.

For any particular site, many different flow process sub-models may be defined and analysed, independently of the system structure sub-model used. The flow process sub-models define the combinations of flow processes to be examined. In comparison to the information available for the definition of system structure sub-models, the information used to define flow process sub-models is frequently both speculative and intuitive in nature. Many different, perhaps conflicting, flow process sub-models thus require examination at the same site. Their complexity can vary from simple sub-models defining only a single flow process, to complex flow combinations involving all the processes allowed for by the model.

MODEL APPLICATION

Unlike *Calver and Cammeraat [1993]* and others, it was not the intent of this study to demonstrate the applicability of the utilised model for general hydrological applications, or to provide evidence of the suitability of particular model simplifications. The approach described here was thus unconventional in that a numerical model was used as a tool for process identification only. The QSOIL model utilised was well suited to such an application, because it is formulated on exact and stringent momentum and continuity criteria. This investigation was also not limited to a single model definition, but was based on an analysis of the results obtained with different and sometimes conflicting model concepts. Hereby the plausibility of flow processes, which are assumed to occur in natural catchments, could be assessed.

The extensive measurements made during the experiments defined rigorous criteria for the evaluation of the modelling results. Not only was a correlation of the simulated flows strived for, but the soil water pressure changes were required to be equally well simulated. As only very specific model structures and assumptions were able to satisfy these criteria, it seems likely that the resulting processes modelled represented those which occurred during the experiments fairly accurately. By indicating erroneous assumptions, valuable information was also obtained from model concepts with which the observed flows and soil water pressure changes could not be modelled simultaneously.

The number of flow process sub-models examined depended on the particular site under investigation. Different characteristics could be assumed for the five main flow processes incorporated in the QSOIL model, e.g. macropores occurring only in the upper soil only or macropores extending to full soil depth. Hereby a significant number of potential process combinations were often obtained, all of these being theoretically equally plausible. Analysis of the experimental measurements helped to reduce the number of process sub-models which needed to be investigated, e.g. for experimental results indicating the influence of macropores on infiltration, only sub-models allowing for some type of macropore flow were taken into consideration.

To validate the models obtained in the model selection procedure, these were applied to other experiments at the same site. Process similarity with those deduced from the analysis of the experimental results, was assumed to provide evidence of model validity.

PROCESS IDENTIFICATION

Flow process identification is largely the result of the iterative procedure which is employed to identify feasible flow process sub-models for the site being examined. This procedure, which is at the core of the proposed approach, is described here for Willerzell Mulde.

Five different flow process sub-models of increasing complexity, were deemed to be realistic for this site on the basis of the experiment analysis. These five sub-models A to E are schematically illustrated in Fig. 7. In general, flow process sub-models were applied in QSOIL using the parameter values determined independently on the basis of the soil property measurements made. Due to the uncertainties pertaining to, and the variability to be expected in these values, especially for the macropore system, some parameter variation was tolerated. Only the sub-models which were not rejected on the basis of their requiring excessive parameter adaption are shown in Fig. 7.

For the flows alone, good correlation between the measured and calculated values could be obtained with all these models using realistic, but somewhat different, parameter values. The suitability of the sub-models could however be determined by comparing the calculated pressures over the entire hillslope to those measured during the experiments. In Fig. 8 such comparisons are shown for the five sub-models examined for a selection of four locations, which approximate the overall hillslope flow response. The values of the instrument cluster around Piezometer P3, i.e. T2, T5 and P3, indicate the average depth dependent response of the system, and the Piezometers P1 and P3 reflect the longitudinal system reaction.

Although the measured pressure changes could not be modelled precisely with any of the sub-models examined, some model calculations portrayed the overall pressure changes more accurately than others. Sub-models which modelled infiltration characteristics different to those measured could be eliminated at this stage. The characteristics of the modelled pressure changes were used to evaluate the plausibility of the remaining sub-models. Numerical goodness-of-fit techniques were not applied, as these could lead to incorrect interpretations on model suitability, i.e. the trends shown in the calculated pressure values were

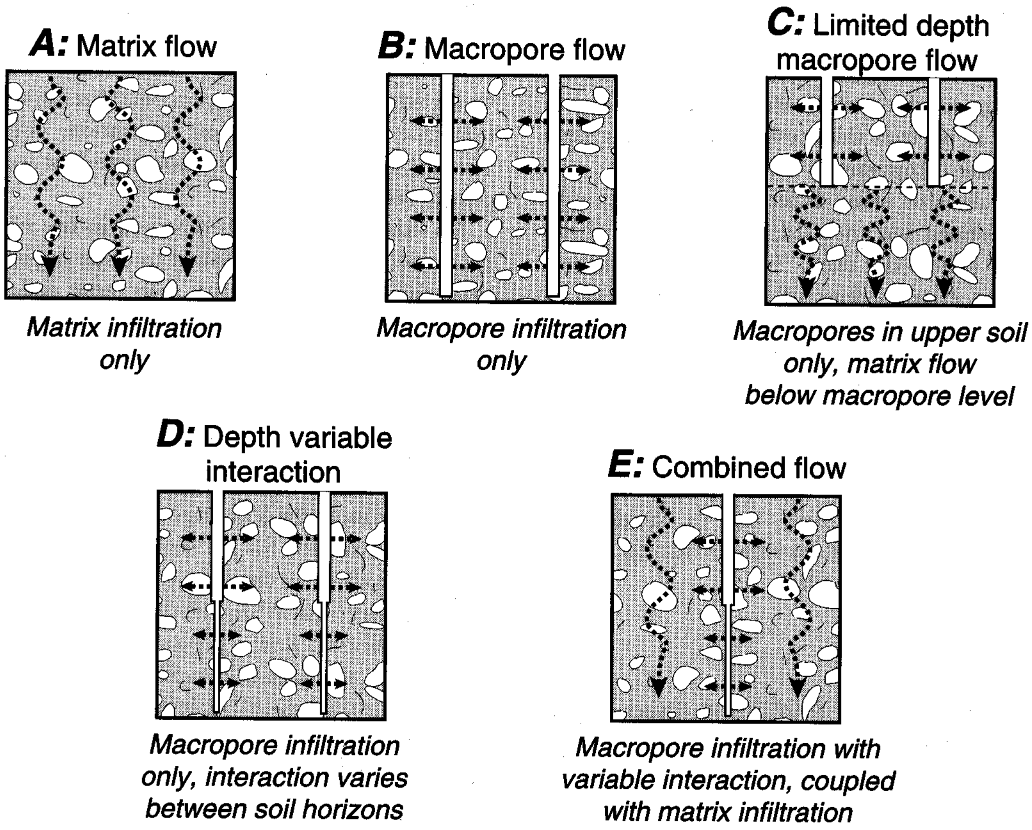


Fig. 7 *Flow process sub-models, describing different infiltration processes, examined for Willerzell Mulde.*

held to be of greater value as validity criteria than absolute deviations from the measurements.

With matrix flow only (Sub-Model A), the best correlation for the most shallow Tensiometer T2 was obtained. However, practically no pressure change was calculated at the remaining, deeper, instrument locations. Matrix flow was therefore not solely responsible for infiltration at Willerzell Mulde as water reached the lowest soil horizons more rapidly than would have been possible with the steady downward progression of a wetting front through the matrix alone.

To enable the rapid downward movement of water, a sub-model with macropore flow only (Sub-Model B) was analysed. Here the situation was reversed from that calculated with matrix flow only, i.e. the piezometer response correlated fairly well, but too little water was released into the upper soil, with the result that T2 response was much too gradual. This indicated overestimation of the extent of rapid water transportation to deeper soil levels due to macropore flow with this model.

On the grounds that earthworm burrows were confined mainly to the upper humus soil horizons, and that too little water infiltrated the upper soil, when full depth macropores were simulated, a Sub-Model C with limited depth macropore flow was investigated. The macropores were assumed to extend only 40 cm below the soil surface. Below the macropore level, vertical water movement was simulated as matrix flow. Here a somewhat better tensiometer response, especially for the upper soil (T2) was obtained. By defining matrix flow below the level of the macropores, a response lag of one hour, which was not apparent in the measurements, was introduced for the piezometers. In the light of this incompatibility, and the fact that rust stains marking preferential flow pathways had been identified over the entire soil depth, the assumption that macropores were only effective to a depth of 40 cm did not seem to be representative of the field conditions.

Some plausible process combination, which would allow for macropore flow over the full depth of the soil, while simultaneously enabling rapid pressure changes in the upper soil, had to be sought. Such a system response was obtained with the Sub-Model D, which defined macropores over the full depth of the soil, these having depth variable interaction, i.e. the parameters of interaction were adapted to define greater water transfer to the soil matrix from the upper soil layers than from lower levels. The calculated responses obtained with this model were comparable to the measurements, with the piezometer values correlating especially well.

As no matrix infiltration was assumed in the Sub-Model

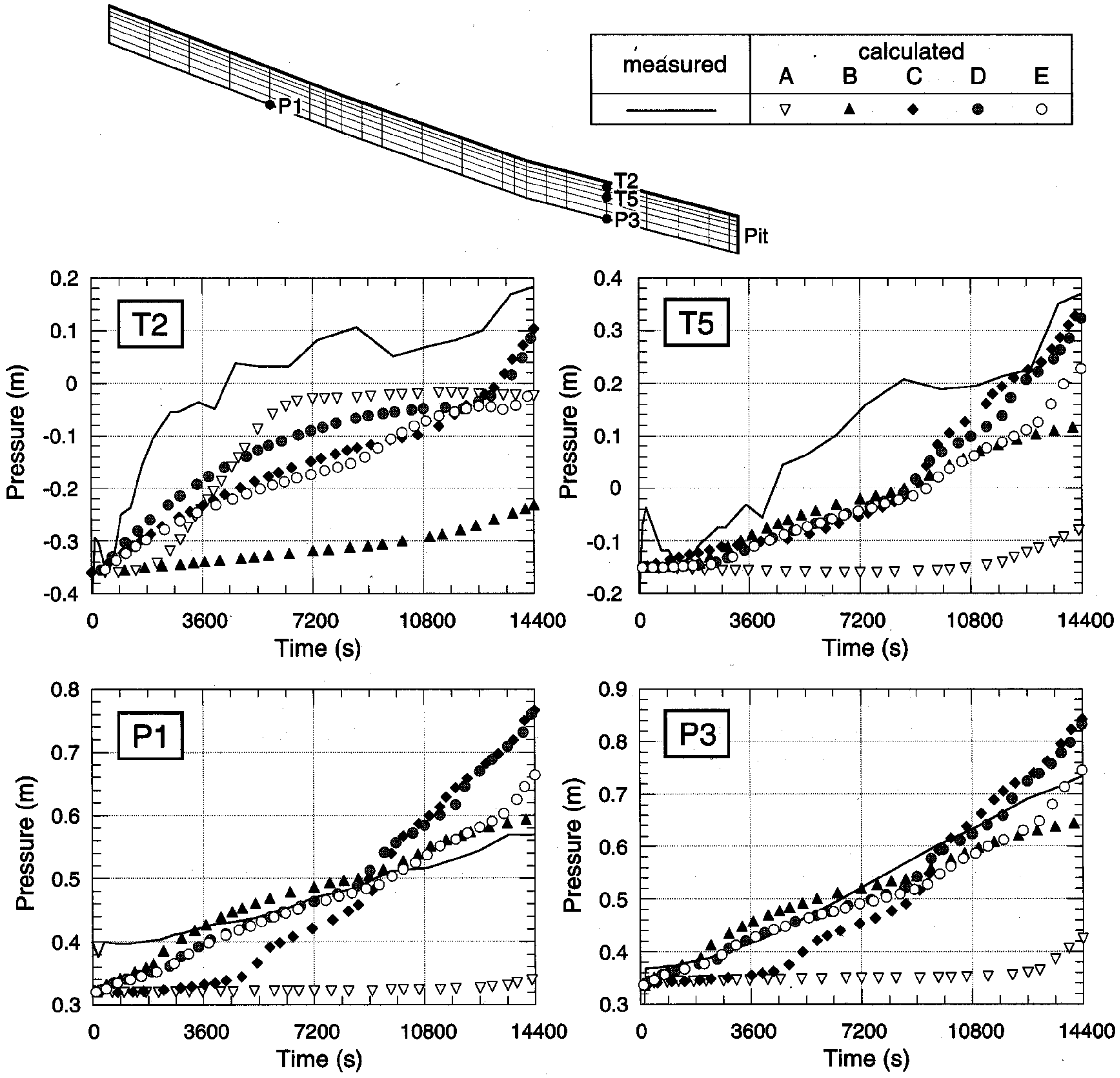


Fig. 8 *Calculated soil water pressure changes and the corresponding measurements of Experiment 47 at four instrument locations (Tensiometers T2 & T5, Piezometers P1 & P3) for the five sub-models examined for Willerzell Mulde (A to E). The equivalent instrument locations in the system structure sub-model are also shown.*

D, it was interesting to see the extent to which the experimental results could still be simulated by allowing for some matrix flow. The Sub-Model E therefore comprised of the combined flow systems, i.e. matrix flow and macropore flow with depth variable interaction. Little difference could be determined between the results obtained with the two Sub-Models D and E. Based on the tensiometer values, the correlation for the Sub-Model D was somewhat better, whereas on the grounds of the piezometer values the Sub-Model E correlation appeared to be slightly better.

A similar sub-model evaluation procedure as described above was applied to all the sites investigated. In most cases a single sub-model resulted, unlike as shown here for Willerzell Mulde, where two different models were obtained which enabled almost equally good simulation of the measurements.

IDENTIFIED INFILTRATION AND FLOW MECHANISMS

The analysis of the simulation results and the parameter adaptations required to calibrate the models, revealed that various phases of flow could be recognised at each site. These phases could commonly be ascribed to different flow processes and mechanisms controlling flow. The end of each phase could usually be attributed to the soil attaining a particular state of saturation. These identified process phases and their characteristics are summarised in Table 1 and illustrated in Fig. 9.

Both poor matrix infiltration and interaction infiltration (as defined in Fig. 1) appeared to have been responsible for the poor infiltration properties observed at Willerzell Mulde. Low matrix infiltration was also responsible for the

Table 1. Processes and control mechanisms of the various flow phases identified for Willerzell Mulde. Although not included in the table, surface storage depletion and surface water film development also occurred during phase 1.

Phase	Duration	Processes occurring	Control mechanism/s for flow observed	End of phase characterised by
1	0–7 (min)	• Filling of macropores extending over full depth of soil	—	Macropore system full
2	7–20 (min)	• Saturation of matrix regions with high conductivity	• Matrix infiltration capacities of individual soil pockets	More conductive matrix pockets saturated
3	20–End (min)	• Filling of soil matrix via macropores principally in the	• Low interaction capacity • Low near surface matrix conductivity	

unexpected macropore activity. Some matrix infiltration possibly occurred during the first minutes of rainfall application, into localised soil pockets with greater conductivity. Such regions of increased matrix infiltrability were to be anticipated on the basis of the heterogeneity observed. Despite the infiltration having taken place mostly via macropores, very little soil water was able to enter the soil as the result of poor interaction. Although the macropore system filled rapidly, very little of this water could be transferred to the soil matrix. The calculations indicated that the interaction capacities were higher in the upper soil regions. It seems possible that this was related to the more frequent presence of water in the hydromorphic lower soil. As described by *Germann [1981]*, minerals supplied by the groundwater may have been deposited along the macropore linings, thereby reducing the interaction capacities.

Conclusions

With the aid of the process identification procedure employed, answers to most of the questions arising from the experimental analysis could be found. Due to the dominance of overland flow at Willerzell Mulde, it was important to identify the causes of poor infiltration. This was found to be primarily due to water not being able to enter the soil matrix. Macropore flow was consequently initiated at the surface, however, due to poor interaction, macropore flow, which was probably responsible for the majority of the subsurface flow, did not significantly contribute to infiltration. Infiltration was in fact insufficient for soil saturation to be attained.

In a similar fashion to that described here, the combined implementation of experimental investigation and numerical simulation also enabled the processes to be identified

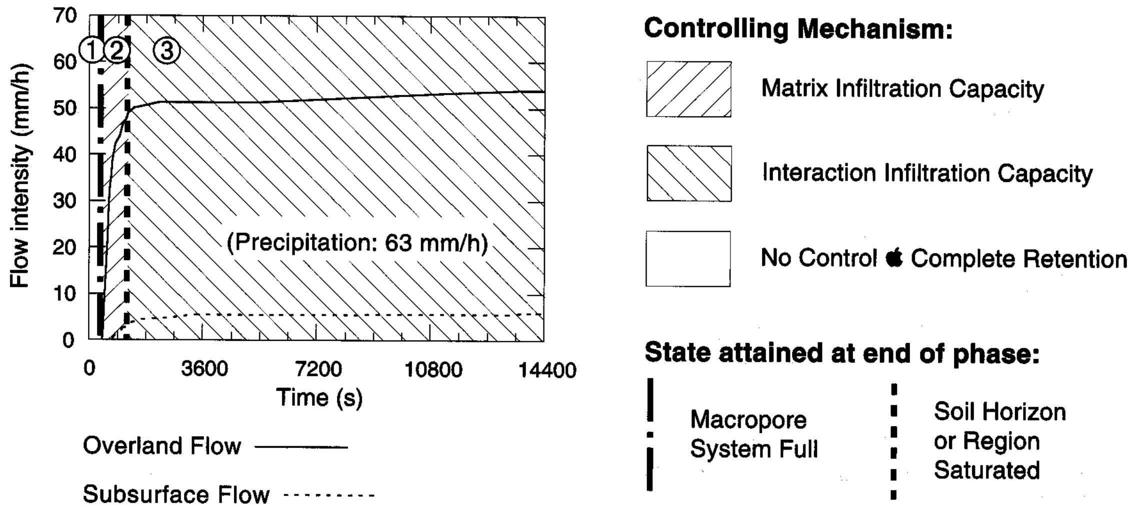


Fig. 9 *The controlling mechanisms responsible for the flows measured at Willerzell Mulde, and the characteristic states marking the transitions between the phases of flow (1 to 3).*

at the other sites examined in this study. The main advantages of this methodology lie therein that experiments are conducted under controlled conditions and thus enable an exact targeting of the processes of interest. The field instruments provide accurate information on the antecedent conditions, enabling accurate evaluation of their hydrological influence. Due to the mobility of the apparatus, a great variety of responses occuring at different sites can also be investigated.

The rigorous nature of QSOIL enables flow process, as they naturally occur in the field, to be simulated. The physical correctness of the computations is ensured by the requirement that both flows and pressure changes be equally well modelled. The flexibility of the model, and diversity of process combinations which can be simulated, facilitates its application for a wide range of differing conditions.

The combined experimental and numerical approach is particularly beneficial for understanding contradictions which arise when field experiments behave in an unexpected manner when compared to the site characteristics. A plausibility analysis of differing possible processes ensures the attainment of a correct process understanding. Hydrological control mechanisms can thereby be isolated and areas for concentrated investigation revealed.

Investigations as described here require a great deal of effort and are certainly not intended for large scale discharge formation analyses. Both the experiments and the numerical simulations can be time consuming. Furthermore, the value and accuracy of the results depends to the a large extent on the expense taken to obtain representative modelling parameter values. The benefits of such detailed investigations are however substantial, and can usually be expected to justify their costs for appropriate investigations.

Acknowledgements

In the wake of the 1987 Reuss River flood, a national research programme on 'Climate Change and Natural Catastrophes' was launched in Switzerland. Funding for the project 'The Role of Catchment Retention on the Magnitude of Floods Following Extreme Precipitation', as conducted at the Swiss Federal Institute of Technology by the authors of this paper, was provided by this programme.

References

Abbaspour K.C. and Schulin R. [1996]: *Two-dimensional flow and transport in unsaturated soils.* Federal Office of Environment, Forests and Landscape (FOEFL), Berne; Environmental Series, No. 259.

Banse H.T. and Graff O.Z. [1968]: Tonverlagerung in den Unterboden entlang Regenwurmröhren. *Mitt. Dtsch. Bodenk. Ges.*, **8**; 223–225.

Beven K.J. and Germann P.F. [1982]: Macropores and water flow in soils. *Wat. Resour. Res.*, **18**; 1311–1325.

Binley A. M., Beven K. J., Calver A. and Watts L.G. [1991]: Changing responses in hydrology: Assessing the uncertainty in physically based model predictions. *Wat. Resour. Res.*, **27**, 1253–1261.

Bouma J. [1981]: Soil morphology and preferential flow along macropores. *Agric. Wat. Manag.*, **3**; 235–250.

Bouma J. [1992]: Effect of soil structure, tillage, and aggregation upon soil hydraulic properties; In: Wagenet R.J., Baveye P. and Stewart B.A. (eds.) *Interacting processes in soil science.* Advances in soil science, Florida.

Burch G.J., Moore I.D. and Burns J. [1989]: Soil hydrophobic effects on infiltration and catchment runoff. *Hydrol. Processes*, **3**; 211–222.

Calver A. and Cammeraat L.H. [1993]: Testing a physically-based runoff model against field observations on a Luxembourg hillslope. *Catena*, **20**; 273–288.

DeCoursey D.G. [1991]: Mathematical models: Research tools for experimental watersheds; In: Bowles D.S. and O'Connell P.E. (eds.) *Recent Advances in the Modelling of Hydrologic Systems.* Kluwer Academic Publishers; 591–612.

Dixon R.M. and Simanton J.R. [1977]: Water infiltration processes and air–earth interface conditions; In: Morel-Seytoux H.J. (ed.) *Surface and Subsurface Hydrology.* Third International Hydrology Symposium, Fort Collins, Water Resources Publications.

Dunne T. [1983]: Relation of field studies and modeling in the prediction of storm runoff. *J. Hydrol.*, **65**; 25–48.

Faeh A. O. [1997]: *Understanding the processes of discharge formation under extreme precipitation, A study based on the numerical simulation of hillslope experiments.* Dissertation ETH Zurich, Nr. 12040.

Faeh A. O., Zuidema P. and Naef F. [ ]: QSOIL: a numerical tool for the identification of hydrological processes. (in preparation).

Gerke H.H. and van Genuchten M.T. [1993]: A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. *Wat. Resour. Res.*, **29**; 305–319.

Germann P. [1981]: Untersuchungen über den Bodenwasserhaushalt im hydrologischen Einzugsgebiet Rietholzbach. *Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie*, Nr. 51.

Grayson R.B., Moore I.D. and McMahon T.A. [1992]: Physically based hydrologic modeling 2. Is the concept realistic? *Wat. Resour. Res.*, **28**, 2659–2666.

Gunzelmann M. [1990]: *Quantification and simulation of the water balance of single aggregates and structured total soils with special regard to the water retention/hydraulic conductivity function of single aggregates.* Ph.D. Thesis (in German), University of Bayreuth, Germany.

Hillel D. [1987]: Unstable flow in layered soils: A review. *Hydrol. Processes*, **1**; 143–147.

Hornberger G.M., Beven K.J. and Germann P. [1990]: Inferences about solute transport in macroporous forest soils from time series models. *Geoderma*, **46**; 249–262.

Lehnardt F. [1985]: Einfluss morpho-pedologischer Eigenschaften auf Infiltration und Abflussverhalten von Waldstandorten; In: *DVWK Schriften Nr. 71, Beiträge zu Oberfächenabfluss und Stoffabtrag bei künstlichen Starkniederschlägen.* Verlag Paul Parey.

Lynch J.A., Corbett E.S. and Sopper W.E. [1977]: Effects of antecedent soil moisture on stormflow volumes and timing; In:

Morel-Seytoux H.J. (ed.) *Surface and Subsurface Hydrology.* Third International Hydrology Symposium, Fort Collins, Water Resources Publications.

Naslas G.D., Miller W.W., Gifford G.F. and Fernandeź G.C.J. [1994]: Effects of soil type, plot condition, and slope on the runoff and interrill erosion of two soils in the lake Tahoe basin. *Wat. Resour. Bull.*, **30**, No. 2. American Water Resources Association,

Nielsen D.R., van Genuchten M.T. and Biggar J.W. [1986]: Water flow and solute transport processes in the unsaturated zone. *Wat. Resour. Res.*, **22**; 89S–108S.

Philip J.R. [1991]: Hillslope infiltration: Divergent and convergent slopes. *Wat. Resour. Res.*, Vol. 27, 1035–1040.

Protopapas A.L. and Bras R.L. [1991]: Analytical solutions for unsteady multidimensional infiltration in heterogeneous soils. *Wat. Resour. Res.*, **27**, 1029–1034.

Rawls W.J. and Brakensiek D.L. [1985]: Prediction of soil water properties for hydrologic modeling; In: Jones E.B. and Ward T.J. (eds.) *Watershed Management in the Eighties.* Proc. of Symp. sponsored by Comm. on Watershed Management, I & D Division, ASCE, ASCE Convention, Denver, CO, April 30–May 1; 293–299.

Reynolds W.D. and Elrick D.E. [1986]: A method for simultaneous in situ measurement in the vadose zone of field-saturated hydraulic conductivity, sorptivity and the conductivity-pressure head relationship. *Groundwater Monitoring Review*, **6**, Winter; 84–95.

Römkens M.J.M., Prasad S.N. and Whisler F.D. [1990]: Surface sealing and infiltration; In: Anderson M.G. and Burt T.P. (eds.) *Process Studies in Hillslope Hydrology.* Wiley, Chichester, UK.

Scherrer S. [1996]: *Abflussbildung bei Starkniederschlägen, Identifikation von Abflussprozessen mittels künstlicher Niederschläge.* Dissertation ETH Zürich, Nr 11793.

Scherrer S., Faeh A.O. and Naef F. [ ]: The variability of the processes of flood formation. (in preparation).

Schoeneberger P. and Amoozegar A. [1990]: Directional saturated hydraulic conductivity and macropore morphology of a soil-saprolite sequence. *Geoderma*, **46**; 31–49.

Smith R.E., Corradini C. and Melone F. [1993]: Modeling infiltration for multistorm runoff events. *Wat. Resour. Res.*, 29., **1**; 133–144.

Steenhuis T.S. and Parlange J.-Y. [1991]: Preferential flow in structured and sandy soils; In: Gish T.J. and Shirmohammadi A. (eds.) *Preferential flow.* American Society of Agricultural Engineers, St. Joseph, Mich.; 12–21.

Thoma S.G., Gallegos D.P. and Smith D.M. [1992]: Impact of fracture coatings on fracture/matrix flow interactions in unsaturated, porous media. *Wat. Resour. Res.*, **28**; 1357–1367.

Weir G.J. and Kissling W.M. [1992]: The influence of airflow on the vertical infiltration of water into soil. *Wat. Resour. Res.*, **28**, 2765–2772.

White R.E. [1985]: The influence of macropores on the transport of dissolved and suspended matter through soil. *Adv. Soil Sci.*, **3**; 95–120.

Zuidema P.K. [1985]: Hydraulik der Abflussbildung während Starkniederschlägen, Eine Untersuchung mit Hilfe numerische Modelle unter Verwendung plausibler Bodenkennwerte. *Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie*, Nr. 79.