NPo-forskning
fra Miljøstyrelsen

Nr. B14 1990

Drainage Flow Modelling - Syv Field Site

Miljøministeriet Miljøstyrelsen

Danish Research Programme on Nitrogen, Phosphorus and Organic Matter (NPO)

The aim of the NPO Research Programme is to gather knowledge on the decomposition of Nitrogen (N), Phosporus (P) and organic matter (o) in the soil, and on their impact on lakes, watercourses, inlets, groundwater and the sea.

This report is one of a total of about 50 reports to be issued in connection with the implementation of the NPO Research Programme. The National Agency of Environmental Protection (NAEP) is responsible for the programme, under which about 70 NPO projects have been launched, carried out at 25-30 institutions.

In the 1970's and the beginning of the 1980's there was a growing awareness of the threats to life in watercourses etc. presented by discharges of nutrients – and of the risk of nitrate contamination of groundwater. In 1984 a report was prepared, synthesising existing knowledge in this field. The report, known by the name of NPO Report, was published by the NAEP.

To follow up this report the Dansih Parliament took the first steps in 1985 to reduce pollution with nutrients – laying down requirements for storage and application of farm yard manure in the agricultural sector.

For the purpose of improving our knowledge on the impact of nutrients in nature, the Danish Parliament also reserved 50 million DKK for the research programme, running from 1985 to the end of 1990.

The significance of the NPO Research Programme was further underlined with the Danish Parliament's adoption of the Action Plan on the Aquatic Environment in 1987. The results of the NPO Research Programme will play a vital role in the evaluation of the effects of the Action Plan.

To safeguard the technical and economic interests relating to the research activities a steering group was set up, having the overall responsibility for the implementation of the NPO Research Programme. Furthermore, three coordination groups were formed, each of them responsible for one of the three fields: soil and air, groundwater, and surface water.

The reports are published in the series »NPo-forskning fra Miljøstyrelsen« (NPo Research in the NAEP), divided into three sections:

A: reports on soil and air
B: reports on groundwater
C: reports on watercourses, lakes and marine waters.

The NAEP has been secretariat for the research programme. The reports published in this series are edited by the Agency with the assistance of the coordination groups.

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1. Introduction

The objectives of the present project have been to carry out detailed modelling studies of flow and transport processes within the Syv Creek catchment, which was selected as one of the research sites in the NPo research programme. The area at the site represents the geological conditions typically for the eastern part of Denmark, where thick moraine layers (25 m or more) with a high clay content overlay deep artesian aquifers of prequaternary origin. The major part of the water supply in eastern Denmark is extracted from the deep aquifer systems.

The hydraulic conductivity of the clayey moraine layers is very small (of the order 10^{-7} m/s or less), and the vertical flow of water towards the artesian aquifer is therefore in general small (of the order 50 mm/year, see e.g. Refsgaard and Stang, 1981). The major part of the water percolating out of the root zone is diverted towards the creeks partly through the upper water table aquifers and partly through the drainage systems. Hansen (1990a) found that drainage outflow contributes mostly to the discharge in Syv Creek, particularly during high flows, where this component may account for up to 70% of the total discharge. Only an insignificant part of the discharge is due to return flow from the deep artesian aquifer. In a previous investigation within the Suså catchment, which has a similar geological structure as the present catchment, the average upward seepage from the artesian aquifer was estimated to 20 mm/year. For the Syv Creek catchment this flow component may be even less.

Hence, subsurface drainage systems seem to exert a major influence on water flow and transport of nutrients in catchments of glacial origin.

The present modelling study addresses the rainfall-discharge relationship within two drainage catchments located in the Syv Creek catchment. Rather than carrying out a modelling analysis of the whole Syv Creek catchment, which would follow the same approach as reported by Storm et al. (1990) for the regional-scale Langvad Creek catchment and thus probably not lead to any additional insight into the flow behaviour, this study focuses on the local-scale drainage catchments. Data for hourly rainfall, daily potential evapotranspiration, and 15 minutes discharges have been collected within the framework of the NPo research programme, which enables a closer analysis of the phenomena responsible for generation of drainage flow including preferential pathways and spatial variability of hydraulic properties. The study is therefore complementary to the regional-scale catchment modelling study, Storm et al. (1990).

Water samples have been collected for analysis of the concentration of selected solutes including nutrients, Hansen (1990a). However, the sampling has only been carried out bi-weekly which is a time resolution too coarse for validation of modelling transport and transformation of nitrate. Furthermore, the concentration data is corrupted by other sources than leaching from the root zone such as sewage water. In addition, the history of nitrate leaching from the root zone has not been fully explored, which makes a qualified model analysis of the transport processes very uncertain and essentially speculative.

To supplement the present study with respect to the transport problem, a controlled field tracer experiment has been carried out at a site adjacent to the two drainage catchments. By adding a known amount of tracer to the soil surface and subsequently monitoring for tracer concentration in the drainage outlet, this study generates field information which makes a qualified modelling study of the transport and dispersion phenomena in the upper soil horizons possible and hereby also provide information on the pathways and fate of surface-applied fertilizers. This study is reported by Villholth et al. (1990).

The three modelling studies mentioned here are in essence complementary and all therefore contribute to an increased understanding of water flow and nitrate transport in catchments of glacial origin.

2. English Summary

Rainfall-discharge observations

Records of rainfall-discharge observations for two drainage catchments within the greater Syv Creek catchment are analyzed. The observation period is 25 years. The outflow hydrographs from both catchments show a very rapid response to rainfall with peaks in drainage outflow only a few hours after the start of the rainfall event. Such hydrographs may be explained by the existence of preferential flow paths in the soil. Further support for the existence of preferential flow is obtained from three summer rainfall events, where drainage outflow is observed shortly after the onset of rainfall even though the root zone is dried to water contents well below field capacity.

Two-component model

A simplified version of the SHE modelling system is applied to the two catchments. A two-component model for unsaturated flow is developed, where Darcy-type matrix flow is simulated by solving Richards' equation, while bypass flow through preferential flow paths is described by a simple routing to the water table using the concept of bypass ratio. The unsaturated flow component is coupled to a simple groundwater flowdescription.

Spatial variability

The effect of spatial variability of retention properties on drainage outflow has been examined using the data from nine soil profiles within the Syv Creek catchment. By treating the soil profiles as independent unsaturated columns, it is demonstrated that it is not possible to obtain an accurate description of the drainage outflow assuming that any one of the profiles represents the whole catchment. Neither can a satisfactory simulation be obtained by combining the responses based on the retention properties from the two profiles closest to the catchments. The most accurate simulation is obtained by introducing all the available retention data. This analysis suggests that it is important to consider the spatial variability of soil hydraulic properties in order to develop flow and transport models for large-scale unsaturated systems.

Preferential flow

Despite inclusion of the full field-documented retention variability it is not possible to simulate the intermittent drainage flow events occurring in the months before the drains start flowing continuously. Using the two-component flow model for the unsaturated zone it is possible to establish a much closer simulation of the outflow hydrographs, thus supporting the existence of preferential flow paths. Other phenomena may, however, also contribute to the observed flow pattern, such as variations in drain and water table depths over the catchment areas. Separation of the influences of the various phenomena tracer tests is required.

Leaching risk

Yet, there is strong evidence that bypass flow exerts some influence on the drainage flow production. This may also have consequences for nitrate leaching, because preferential pathways provide effective shortcuts between the root zone and the drains, and with the risk that a good part of the fertilizers or manure applied prior to a rainfall event may be leached directly to surface waters and thus lead to increased entrophication problems.

3. Dansk sammendrag

Nedbør og drænafstrømning

Sammenhængen mellem observationer af nedbør og drænafstrømning i Syv bæks opland er analyseret for to drænvandsoplande. Afstrømningshydrograferne for begge oplande udviser et hurtigt respons, hvor afstrømningen når maksimum kun få timer, efter regnen starter. Dette afstrømningsmønster kan forklares ved eksistensen af makroporer i jorden. Specielt har der i den undersøgte periode været tre regnhændelser i sommerperioder, hvor drænene har været aktive. Da jorden har et vandindhold på under markkapacitet i denne periode, kan afstrømningen forklares ved hurtig strømning i makroporer.

To-komponent model

En forenklet version af SHE modellen er blevet benyttet på de to drænvandsoplande. En to-komponent model for umættet strømning er udviklet, hvor Darcy-strømning gennem jorden matricen er simuleret ved en løsning af Richards ligning, og hvor makropore strømning er simuleret ved hjælp af en empirisk model. Den umættede model er koblet til en simpel grundvandsbeskrivelse.

Rumlig variabilitet

Betydningen af rumlig variabilitet i retentionsdata på drænvandsafstrømningen er analyseret ved hjælp af data fra ni jordprofiler fra Syv bæks opland. Det er demonstreret at ud fra en antagelse om, at hver enkelt profil er repræsentativ for hele drænvandsoplandet, kan der ikke opnås en tilfredsstillende modelbeskrivelse af drænvandsafstrømningen. Kombineres den beregnede afstrømning fra to af de profiler, der ligger tættest på drænvandsoplandene, opnås heller ikke en tilfredsstillende beskrivelse. Kombineres derimod den beregnede afstrømning fra alle ni profiler, opnås den bedste beskrivelse af den observerede afstrømning. Det kan derfor påpeges, at det er vigtigt at inddrage den rumlige variabilitet for at kunne beskrive vandstrømning i drænvandsoplande.

Makropore strømning

Selv om den målte variation i retentionsdata blev inddraget i modelsimuleringerne, kunne den første del af drænsæsonen ikke simuleres tilfredsstillende. Ved at anvende en to-komponent beskrivelse af strømningen i den umættede zone var det muligt at opnå en langt bedre beskrivelse af denne tidlige del af drænsæsonen.

Andre fænomener såsom variationer i dybden til drænene og grundvandsspejlet inden for drænvandsoplandene har også betydning for den samlede drænvandsafstrømning.

Udvaskning

Eksistensen af makroporer har også stor betydning for udvaskningsprocessen, fordi de vil kunne optræde som hurtige transportveje for næringsstoffer tilført markerne, lige før en given regn starter.

4. Background

Leaching of nitrate from the root zone is a yearly recurring process in early fall which, in clayey soil types in Denmark, has been thought of as having only a small impact on the surface and groundwater systems due to a high nitrate reduction capacity in the clay soils.

Impact on surface waters

The vulnerability of the surface waters has in many areas increased, because the zone of oxidation has moved to below drain depth. The denitrification process then only has the effect of protecting deeper primary aquifers, while no significant depletion of nitrate in the percolating water occurs before the water enters the drainage systems. Subsurface drainage systems provide an effective shortcut between the water leached from the root zone and the surface waters. High inputs of nitrogen to the surface waters can result in eutrophication problems.

Soil variability

Transport of water and solutes in the upper soil horizons is significantly influenced by the complicated and apparent random composition of the soil. A number of experimental studies (e.g. Nielsen et al. 1973, Byers and Stephens 1983, Russo and Bresler 1983, Jensen and Refsgaard 1989) and theoretical studies (e.g. Yeh et al. 1985 a,b,c, Mantoglou and Gelhar 1987 a,b,c) have demonstrated the magnitude and importance of the spatial variability of soil hydraulic properties, and in order to develop physically plausible descriptions of flow and transport it is important to consider this variability.

Furthermore, many soils have structures arising from drying cracks, earthworm channels, decayed roots, interpedal voids and fractures, which provide preferential pathways (macropores) for water and soluble chemicals to move from the root zone through the unsaturated zone towards the groundwater table as described by e.g. Beven and

German (1982). Hereby there is an increased potential for pollution of groundwater by surface-applied fertilizers and pesticides.

Preferential flow

Preferential flow or bypass is a flow mechanism which in certain cases also can be responsible for high inputs of nitrogen directly from the root zone to surface waters through the drain network. If the zone of oxidation is above drain depth, bypass flow will reduce the residence time in the soil and thus the degree of contact with reducing clay minerals. Further, bypass flow will typically give an earlier start of drainage outflow in the fall, at which time the nitrogen content in the root zone can be rather high. If the nitrogen is readily soluble, a high loss of nitrogen to the surface waters is likely. On the other hand, if nitrogen has already been incorporated into the soil matrix, a dilution effect can occur, because recently infiltrated rainwater bypasses the soil matrix and dilutes the more concentrated porous matrix outflow at the drains. Obviously, both flow mechanisms can occur during the drainage season, Trudgill (1988). The effect of bypass flow has been observed in Danish clay soils, see e.g. Refsgaard (1981), Simmelsgaard (1985) and Jensen & Refsgaard (1989).

Investigations on spatial variability

When large-scale flow and leaching problems in clay soils are considered, both spatial variability of soil hydraulic properties as well as preferential pathways influence the integrated response from the area, and in fact it may be difficult to separate the effect from these two phenomena when interpreting the outflow response. Most of the experimental studies on the variability of natural soil systems have approached the problem by dense sampling of soil cores typically of the size 5-10 cm. The hydraulic properties (retention and hydraulic conductivity) have subsequently been determined on the cores in the laboratory. To estimate the outflow from a large-scale system (e.g. a drainage catchment), the soil has often been conceptualized as consisting of a number of vertical soil columns, and by allocating the measurements of the hydraulic properties to the soil columns, either in a deterministic or stochastic sense, the integrated outflow from the soil system can then be predicted by solving the unsaturated flow equation for each column and subsequently combine the results, see e.g. Bresler and Dagan (1983 a,b), and Jensen and Refsgaard (1989).

By verifying the model simulations against measurements of water content and suction, it is hypothesized that the cumulative outflow predictions from the ensemble of soil columns represent the real world. However, successful comparison to scattered internal measurements of soil water variables do not warrant that the recharge is simulated correctly, because the integrated system response may be influenced in complicated ways by local three-dimensional flow behaviour which is not considered by such a model approach.

Sampling scale

The soil sampling scale also seems to be critical, because this scale may not encompass all the variation that is important to flow and transport in field soils particularly when macropores are present. For such systems the scale of a representative sample is much larger, and furthermore application of a homogeneous Darcy-type flow theory may be a poor representation. The concept of scale and representative elementary volume (REV) has been analysed theoretically by Baveye and Sposito (1984) and Cushman (1984).

Even though a more appropriate soil sampling scale was adopted, it would still be an impractical task to sample so densely that the hydraulic behaviour of the unsaturated zone system can be deterministically defined in all details. Some statistical techniques may be used to aggregate the sample results; however, predictions of the recharge of water and solutes to the groundwater may still be rather uncertain.

Tile drain
collector

A sampling device which can provide information on the cumulative recharge and contamination load from a large-scale soil system is provided by tile drain systems. Tile drains, which are commonly installed in agricultural fields to improve cultivation conditions, collect water near the water table and therefore represent the recharge from the unsaturated zone. By draining large volumes of soil and conveying it out of the system through a single outlet, tile drains represent the integrated response of large-scale flow and transport through the unsaturated zone. Obviously, small variations in recharge characteristics arising from soil heterogeneity or preferential flow paths are to a certain degree filtered out, and the outlet response in itself does not provide detailed information on the processes taking place in the system. However, by interpreting the response in combination with model simulations, it is possible to assess the significance of spatial variability and preferential pathways on the flow behaviour. Richard and Steenhuis (1988) have previously reported on tile drains as a large-scale instrument for preferential flow analysis.

Field data has been obtained from two drainage catchments in Denmark, where time series of rainfall, evapotranspiration and discharge as well as scattered measurements of soil properties are available. The size of both catchments is 55 - 60 ha.

Modelling approach

The SHE-model (Abbott et al. 1986) has been used for analyzing the rainfall-discharge relationship of the two catchments. The model is used in a simple mode by applying only one grid element in the groundwater model and introducing a linear routing description for the flow in tile drains, while emphasis has been devoted to the flow modelling of the unsaturated zone including the root zone.

Emphasis of study

The study has the objective to investigate the influence of soil heterogeneity and preferential flow on the rainfall-discharge relationship using a very simplistic model approach, but on the other hand compare and analyze the predictions against reliable real-life data. The study does not attempt to develop or improve the mechanistic process descriptions of these two flow problems, but it is more an attempt to address these problems through a parameter sensitivity analysis using a simple model analysis.

5. Field site observations

Field site

The Syv Creek field site, Fig. 1, was established in 1987 in order to investigate the impact of nitrate leaching to surface water and groundwater systems. Specifically, the outflow through the drainage systems to the Syv Creek was of interest.

In Ernstsen et al. (1990) a detailed description of the geological, geochemical, and hydrological investigations is given. The discharge from two drainage catchments (55 - 60 ha) as monitored from the autumn of 1987 to the summer of 1990.

Catchment 1 is characterized by a relatively flat topography, while catchment 2 has a moderate plane averaged slope of approximately 1.5 %.

The primary chalk aquifer is protected by a 20 - 25 m thick moraine clay layer. The front separating the nitrate oxidation and reduction zones has been observed at 2 - 3 m depth (Ernstsen et al., 1990) which leaves a large reduction capacity for nitrate infiltration below drain depth.

Soil characteristics

At 10 locations in the larger Syv Creek catchment (1170 ha) soil samples at several depths were taken for classification and measurement of retention characteristics, Afd. for Arealdata og kortlæging (1990). Measurements from nine of the sampling locations are used in the present analysis, Fig. 2 (only eight shown here).

Saturated hydraulic conductivity was not measured, but has been estimated on the basis of measurements on similar soils, Jensen & Refsgaard (1989).

Worm and root channels were observed at a density of 1-10 per square decimeter in most of the samples suggesting that not only are the preferential flowpaths present, but they also have some degree of connectivity.

Rainfall

Rainfall was measured at the climate station shown in Fig. 1 and amounted in 1988-89 to 6 - 700 mm/year resulting in a cumulative drain outflow in both catchments of approximately 40% of the amount of rainfall. Potential evapotranspiration was estimated using the Makkink equation (Olesen, 1990) on the basis of climatic variables also measured at the climate station.

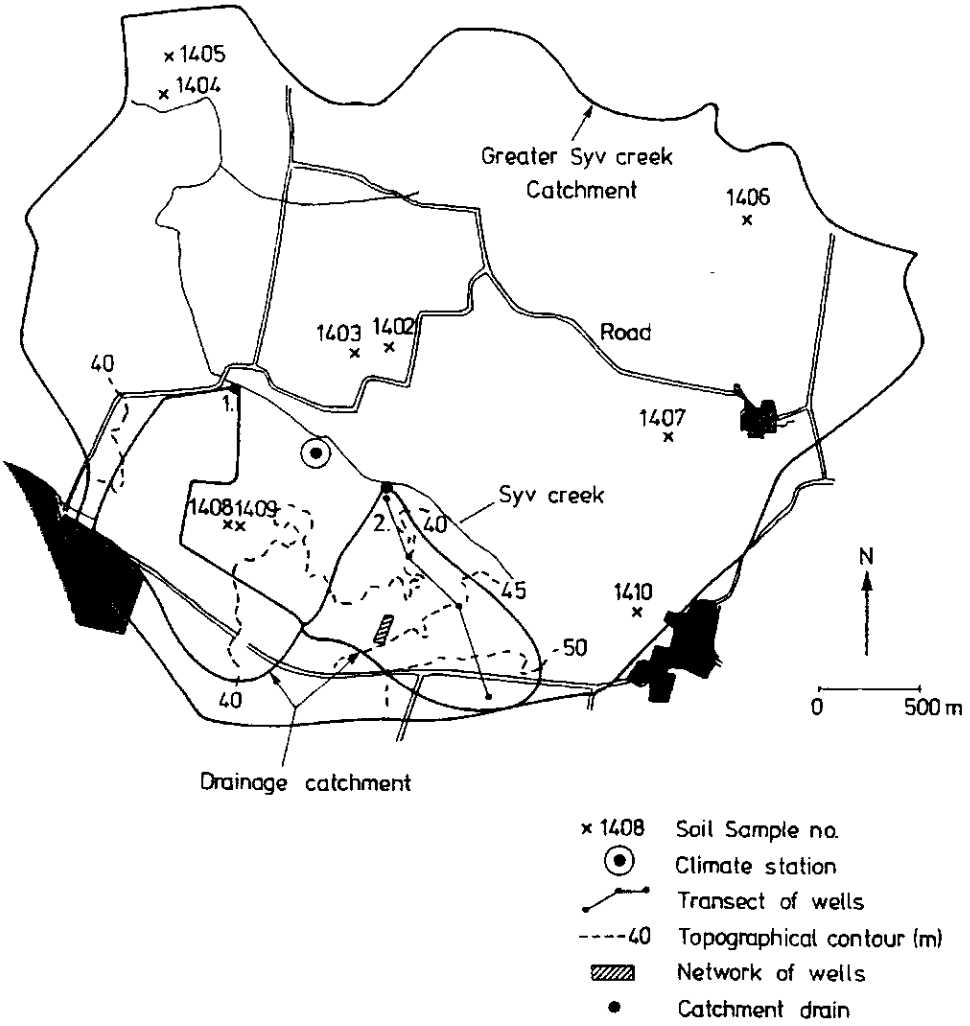


Figure 1

Syv Creek field site.

Drainage flow

Both drain outlets were monitored continuously all year long, Hansen (1990a). The drainage outflow hydrographs show a very rapid response with peaks in drainage outflow only few hours after the start of the rainfall event. Such hydrographs may be explained by the existence of preferential flow paths in the soil. A further support of the existence of bypass flow is obtained from three summer rainfall events, where drainage outflow is observed shortly after the onset of rainfall even though the rootzone is dried to a water content well below field capacity. Fig. 3 shows the drain outflow hydrographs from both catchments and the rainfall intensity distribution from a selected July rainfall event. Although the soil is relatively dry at that time, bypass flow is probably produced, resulting in drain outflow peaks shortly after the rainfall intensity peaks. Syv Creek receives most of its water from the drain outlets, the base flow being very low except after periods with significant amounts of rainfall.

Drain water quality

The drain water quality was measured biweekly, Hansen (1990a). Nitrate concentrations averaged 11 - 12 mg $\mathrm{No_3}$-N/l apparently with small fluctuations. Total amount of nitrate drained was estimated to 40 - 43 kg $\mathrm{No_3}$-N/ha in 1988 of which 90% occurred in the period December - April. In 1989 this amount was much smaller due to an unusually dry winter 1988-89.

Groundwater

The ground water table was monitored monthly at three drain sub-networks and in the winter of 1990 along a transect. The location of the networks and the transect is shown in Fig. 1. At the networks, a large seasonal fluctuation was observed, occasionally with flooding. However, during the drainage season the water table was located approximately 0.7 - 1.1 m below soil

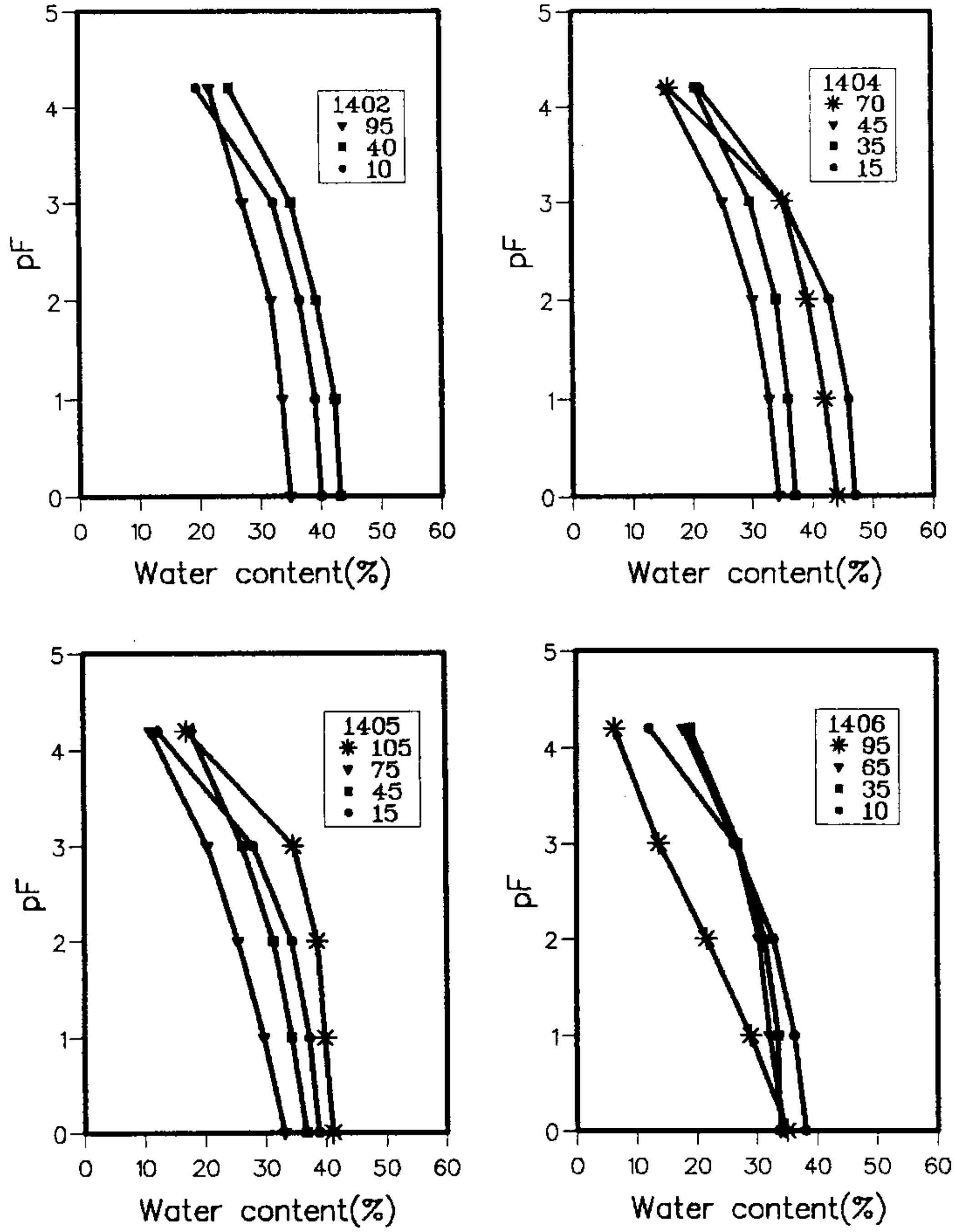


Figure 2

Retention characteristics, Afd. for Arealdata og Kortlægning (1990).
Each curve represents a given depth in cms.

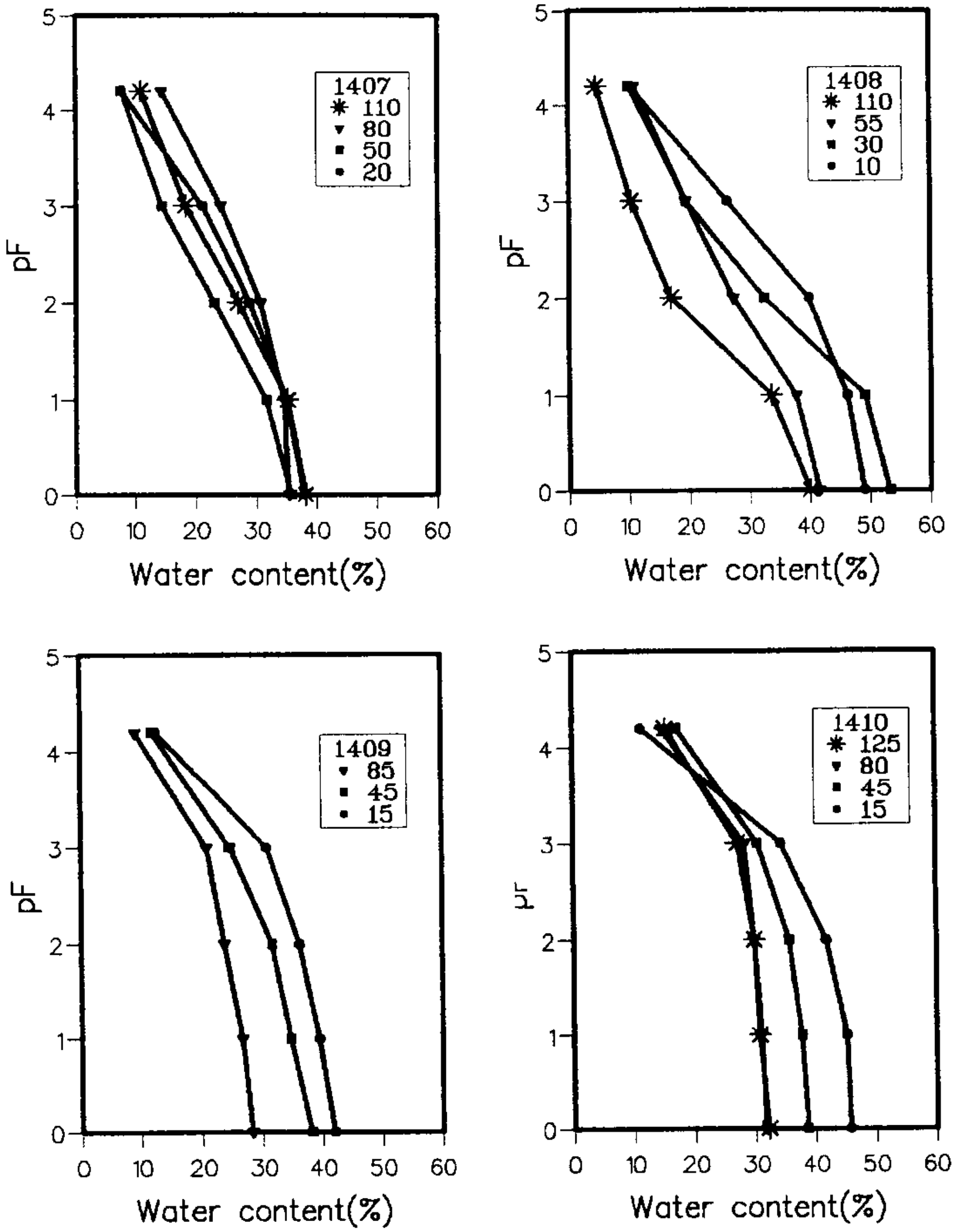


Figure 2, contd.

Rentention characteristics, Afd. for Arealdata og Kortlægning (1990). Each curve represents a given depth in cms.

surface. An averaged hydraulic gradient of 1.3 % towards Syv Creek was determined from the water table observations along the transect.

Vegetation

In the larger Syv creek catchment (1170 ha), 91% of the area is used for farming primarily growing wheat and barley (49%) and rape (20%), Hansen (1990b).

6. Flow model description

Modelling approach

In the first model analysis each drainage catchment is treated as an equivalent one-

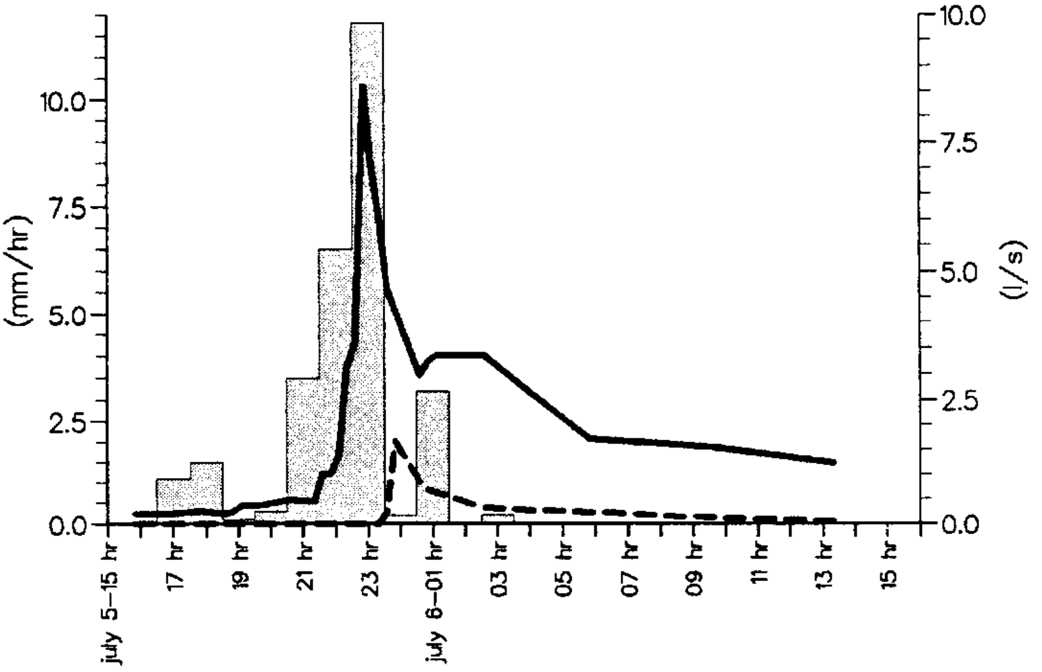


Figure 3
Rainfall intensity (mm/hr) shown as bars and drainage discharge (l/s) from catchment 1 (dashed line) and 2 (solid line) during a July storm.

dimensional soil column. The unsaturated zone component of the SHE modelling system, Abott et al. (1986), extended with an empirical description for bypass flow together with a simple groundwater and river flow description is used to simulate movement of water through the unsaturated zone and the subsequent discharge to the creek either through the drains or from the groundwater, Fig. 4. A similar approach of treating the entire system as an equivalent one-dimensional system was recently used by Gerritse & Schofield (1989) in investigating phosphate movement in soils. In addressing the influence of spatial variability on the simulated drain outflow, the catchment is hypothesized as consisting of a number of independent soil columns, and the total outflow is then obtained by combining the outflow responses from all columns on an equal weight basis. A similar approach was used by Bergstrøm & Brandt (1987) in studying nitrate leaching from field soils.

Unsaturated flow equation

For simulating Darcy-type unsaturated flow, the Richards equation for one-dimensional flow is solved:

$$C \frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z} \left(K \frac{\partial \phi}{\partial z} \right) - \frac{\partial K}{\partial z} - S \qquad (1)$$

where

ϕ - capillary pressure
C - water capacity
K - hydraulic conductivity
S - sink term representing evapotranspiration
z - vertical coordinate, positive downwards
t - time

Hydraulic conductivity function

The hydraulic functions required to solve this equation are the retention function (here assumed to be non-hysteretic) and the hydraulic function,

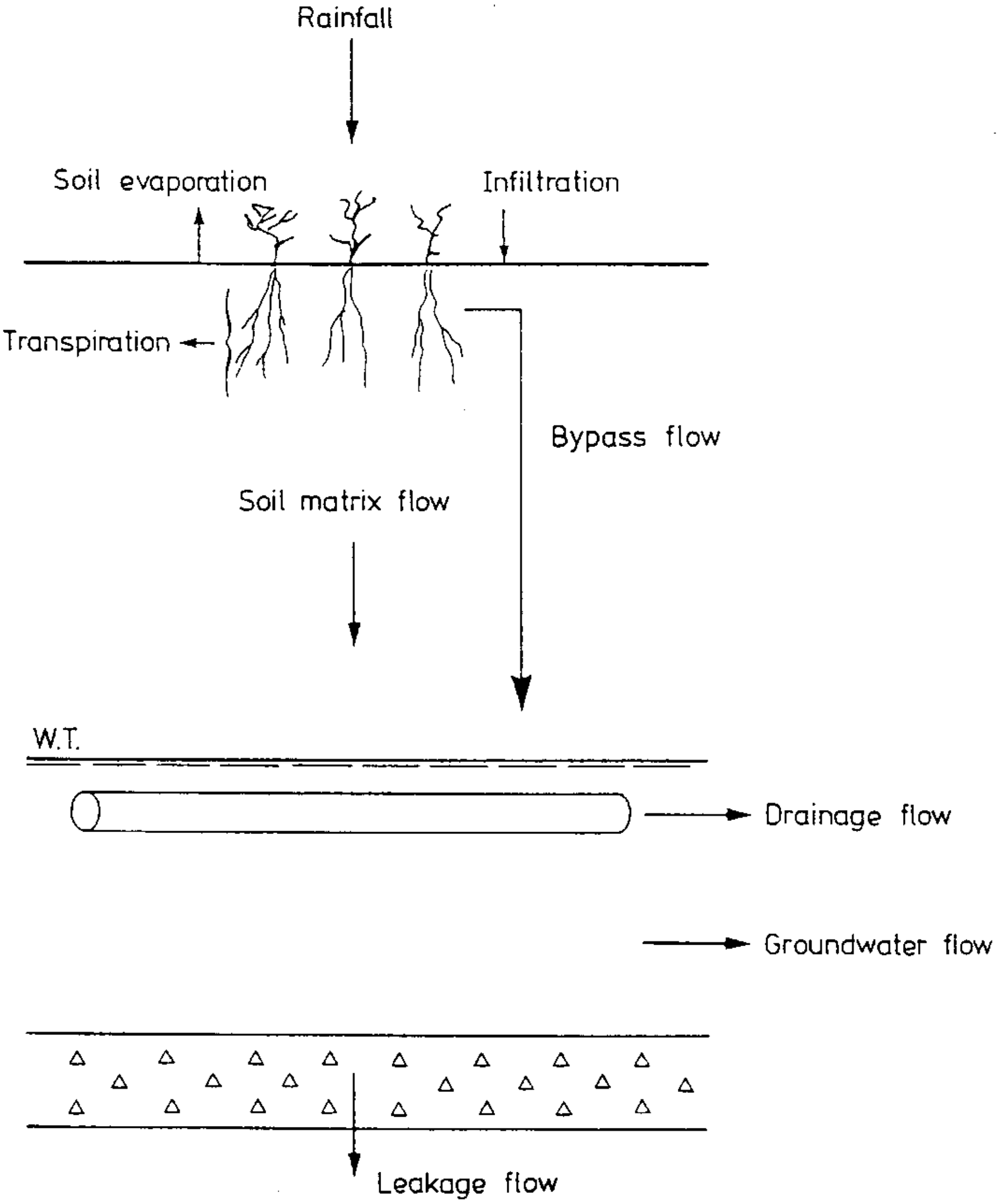


Figure 4
Flow model components.

which is represented by a power function of the following form

$$K(\theta) = K_s \left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^n \qquad (2)$$

where

$K(\theta)$ - hydraulic conductivity
K_s - hydraulic conductivity at saturation
θ_s - water content at saturation
θ - water content
θ_r - residual water content
n - exponent

The residual water content is the value where the hydraulic conductivity effectively is set to zero. It is here assumed that this water content corresponds to a pF-value of 3.0. The exponent n is calibrated such that the hydraulic conductivity at field capacity , which also is obtained from the retention curve at a pF-value of 2.0, is very low (here assumed to be 0.1 mm/day).

Evapotranspiration

The evapotranspiration depleting the water storage in the root zone is predicted on the basis of data for daily potential evapotranspiration. This amount is divided into a fraction available for soil evaporation and a fraction available for transpiration, which depending on the water content in the root zone is reduced before entered into the sink term of the flow equation.

The diffential flow equation is solved by finite difference techniques with the rainfall as the upper boundary condition (flux) and the location of the water table as the lower boundary (pressure). For further details of the model including the parametric values for the evapotranspiration parameters, reference is made to Jensen and Refsgaard (1989).

Two-domain model

The outflow hydrographs from the two drainage catchments strongly indicate that the water flow through the unsaturated zone is influenced by the existence of preferential pathways thus invalidating a uniform Darcy-type flow description. A common approach to modelling flow in structured soils has been a two-domain concept, where the porous medium is considered to consist of two components, one representing the preferential pathways of macropores and cracks and the other the surrounding soil matrix, with its relatively smaller pores.

The two-domain concept has been adopted in this study. To describe the flow in the soil matrix Richards formulation as discussed above is assumed, while bypass flow through preferential flow paths is introduced according to the following empirical relations:

$$\begin{aligned} q_b &= 0 , && \theta < \theta_r \\ q_b &= f_b \cdot P \cdot \left(\frac{\theta-\theta_r}{\theta_{fc}-\theta_r}\right) , && \theta_r < \theta < \theta_{fc} \\ q_b &= f_b \cdot P , && \theta > \theta_{fc} \end{aligned} \qquad (3)$$

where

q_b - bypass flow to water table
f_b - empirical bypass ratio
P - rainfall
θ - water content (5 cm below soil surface)
θ_{fc} - water content at field capacity
θ_r - residual water content

To emphasize the empiricism of this formulation we shall use the term bypass flow as opposed to the more physically based macropore flow models (see e.g. Beven and Germann, 1987 and Jarvis and Leeds-Harrison, 1987 a,b).

Bypass flow

Bypass flow is routed directly to the water table, and the amount of rainfall available for infiltration into the soil matrix is consequently reduced by the same amount.

The bypass model resembles the combined model proposed and successfully tested by Trudgill & Coles (1988) and the model by Stiphout et al. (1987), where initiation and amount of bypass flow is dependent on antecedent soil moisture content, rainfall intensity, and infiltration capacity.

In the model represented by Eqs. 3, when $\theta > \theta_{fc}$, bypass flow is determined by a bypass ratio expressing how much of the rainfall will bypass the soil matrix and be routed directly to the groundwater table. When $\theta < \theta_{fc}$, the amount of bypass flow decreases linearly as a function of moisture content and is zero below residual moisture content. The model differs from the combined model of Trudgill & Coles (1988) in that it does not consider an infiltration threshold value, which can be difficult to estimate and furthermore is a function of time as discussed by the authors. In their model, when $\theta > \theta_{fc}$, bypass flow always occurs irrespective of rainfall intensity, while for $\theta_r < \theta < \theta_{fc}$ only rainfall intensities greater than the threshold value will produce bypass flow. The amount of bypass flow is determined as that in excess of the threshold value.

The bypass model here uses an empirical parameter, the bypass ratio, which is an unknown function of the infiltration capacity of the soil and the density and connectivity of the preferential flow paths. For the same soil, experimental determination of the bypass ratio has shown that it is a function of application rate as demonstrated by Kneale & White (1984), and thus during a rainfall event also a function of time. Stiphout et al. (1987) use a threshold value to initiate bypass flow irrespective of the antecedent moisture content, and they introduce a bypass ratio function which linearly decreases the amount of bypass as a function of pressure head. The main difference between their model and that represented by Eq. 3 and the one proposed by Trudgill and Coles (1988) is that bypass flow is not initiated at intensities below a certain threshold even though $\theta > \theta_{fc}$.

The merits of the model proposed here are mainly related to its simplicity. Bypass flow is a constant fraction f_b of rainfall for water contents above field capacity, while this fraction is reduced linearily for water contents between field capacity and residual. Note that bypass flow hereby is predicted even for water contents below field capacity as observed by Reid & Parkinson (1984). The assumption of direct bypass flow to the groundwater table is supported by the fact that the clay soil is very wet during the drainage season, and lateral absorption into the porous matrix is therefore negligible. One of the elements of the model that can be critisized is obviously the parameter f_b which, in some sense, is a time-averaged value and must be assessed through calibration.

Drainage and groundwater flow

The unsaturated zone component is coupled to a simple groundwater flow description where outflow through the drains is treated as a linear reservoir with a characteristic time constant. The storage is determined by the amount of water above drain level, and the time constant represents the routing time of water from the reservoir out through the drains. The baseflow of groundwater to Syv Creek is calculated from Darcy's law by specifying the boundary condition for the water level in Syv Creek such that the hydraulic gradient between the two systems compares to observations, and similarly a representative hydraulic conductivity is specified. The flow of water from the upper water table aquifer to the deeper confined aquifer is assumed to be constant over the season (40 mm/year), see Refsgaard and Stang (1981).

Analysis of effect of spatial variability

As discussed previously a significant spatial variability of soil parameters can be expected within the two drainage catchments. We have analyzed this problem in a somewhat simplistic manner by applying the model to the set of retention data available from the study area and subsequently combined the individual outflow responses to represent the integrated outflow from the drainage catchments.

In case 1, retention data from only one location are applied assuming that the data are representative for the whole area. Two sets of retention curves measured at the two locations closest to the drainage catchments are tested.

In case 2, the two sets of retention data from case 1 are now assumed to represent half of the drainage area, and the total drainage outflow is thus obtained as the equally weighted sum of the two individual responses.

In case 3, all nine sets of retention curves (representing the larger Syv creek catchment) are included, each representing 1/9 of the outflow response.

7. Results and discussion

Calibration

The values of the parameters used for calculating evapotranspiration and drainage outflow were estimated from Refsgaard (1981) and Jensen and Refsgaard (1989). The sensitivity of some of these empirically based parameters as assessed through several calibration runs. Particularly it was found that the outflow response was somewhat sensitive to variations in the time-constant of the linear reservoir describing the drainage outflow. For all the simulation results presented below a value of 30 days has been used for the time constant.

Leaf area index and root depth are both needed for calculating evapotranspiration, and since no detailed measurements were available, a generalized seasonal variation was specified assuming that wheat is representative for most of the catchment areas.

7.1 Simulation cases 1

Figs. 5 and 6 compare measured and simulated drainage outflow for catchment 2 where the simulations are based on retention information from only one sampling profile. The two sampling locations, 1408 and 1409, closest to the drainage catchments are considered.

Presentation of results

The diagrams included in the figures illustrate, in addition to the drainage outflow, daily rainfall, predicted mean daily potential and actual evapotranspiration, predicted water content in the unsaturated zone and observed and predicted water table elevation. Only the drainage seasons 1987-88, 1988-89 and 1989-90 are shown.

Drainage flow

Both simulations clearly demonstrate that the simulated drainage flow starts about two months later than observed. Profile 1409 has a higher clay content than profile 1408 and therefore a higher water-holding capacity with a smaller drainable porosity (steeper retention curve). The water flow through this profile is therefore more dominated by displacement processes, which lead to a more fluctuating response and in some way a more reasonable simulation than for profile 1408, where a considerable suppression of the response takes place. Simulations based on the other soil profiles possess the same deficiencies as the ones presented here by not capturing the onset of the drainage season, which is important from a nitrate-leaching point of view, while the higher discharges are simulated more or less accurately depending on the individual retention characteristics.

Water table

The discrepancies discussed above are also reflected in the simulation of the water table fluctuations which are compared to observations in the bottom diagram of the figures. Based on monthly measurements of the water table fluctuation (Ernstsen et al., 1990) within a subarea of drainage catchment 2 (cf. Fig. 1), the minimum, maximum, and average water table depths have been estimated and shown in the diagram. Due to various measurement problems particularly during extreme low-level and high-level conditions, the three levels shown are rather uncertain. Furthermore, the groundwater flow modelling approach applied in the present study is simple and essentially only consists of one grid element in the numerical groundwater flow model. Hence, a detailed comparison between predictions and observations of water table fluctuations

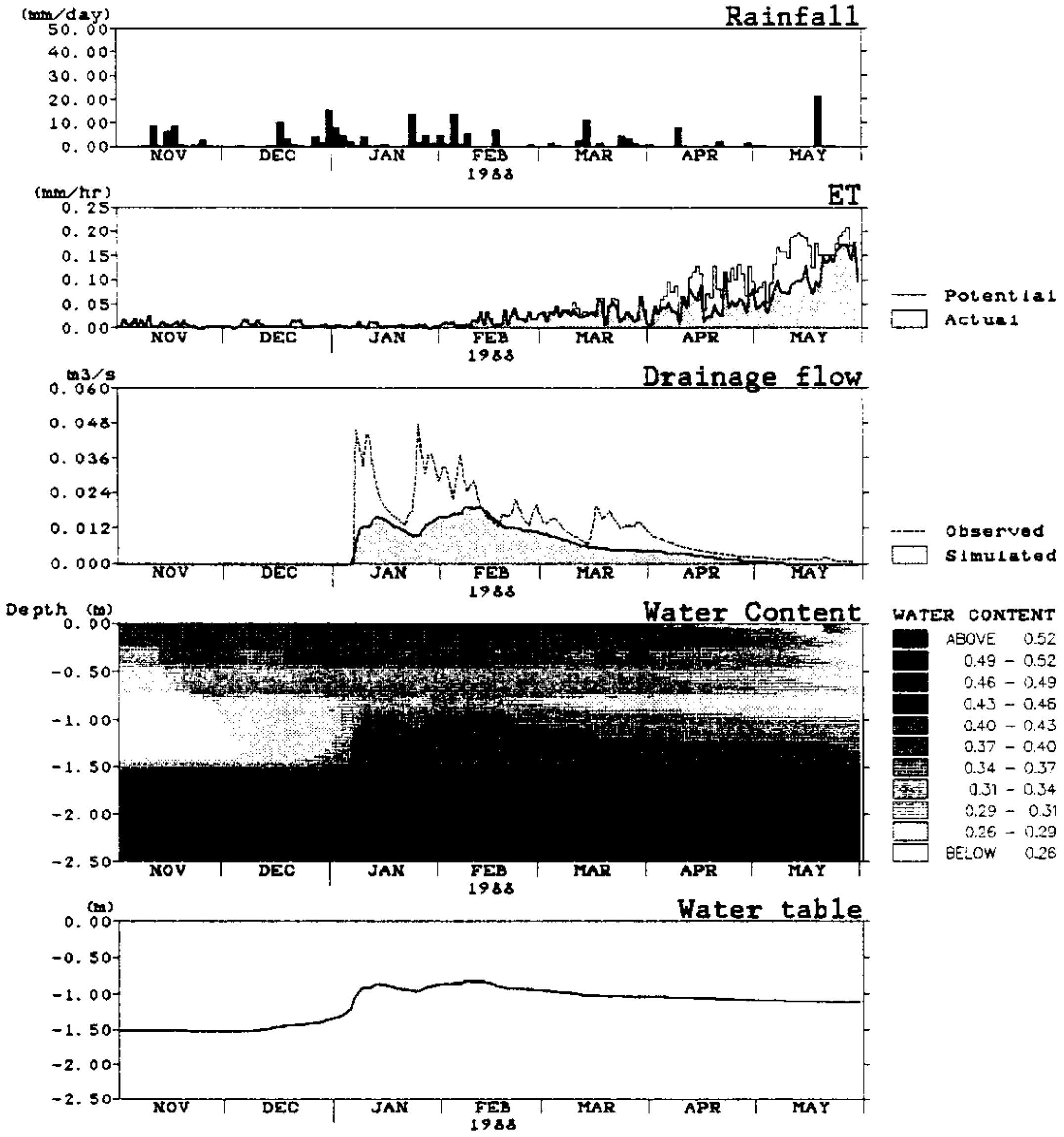
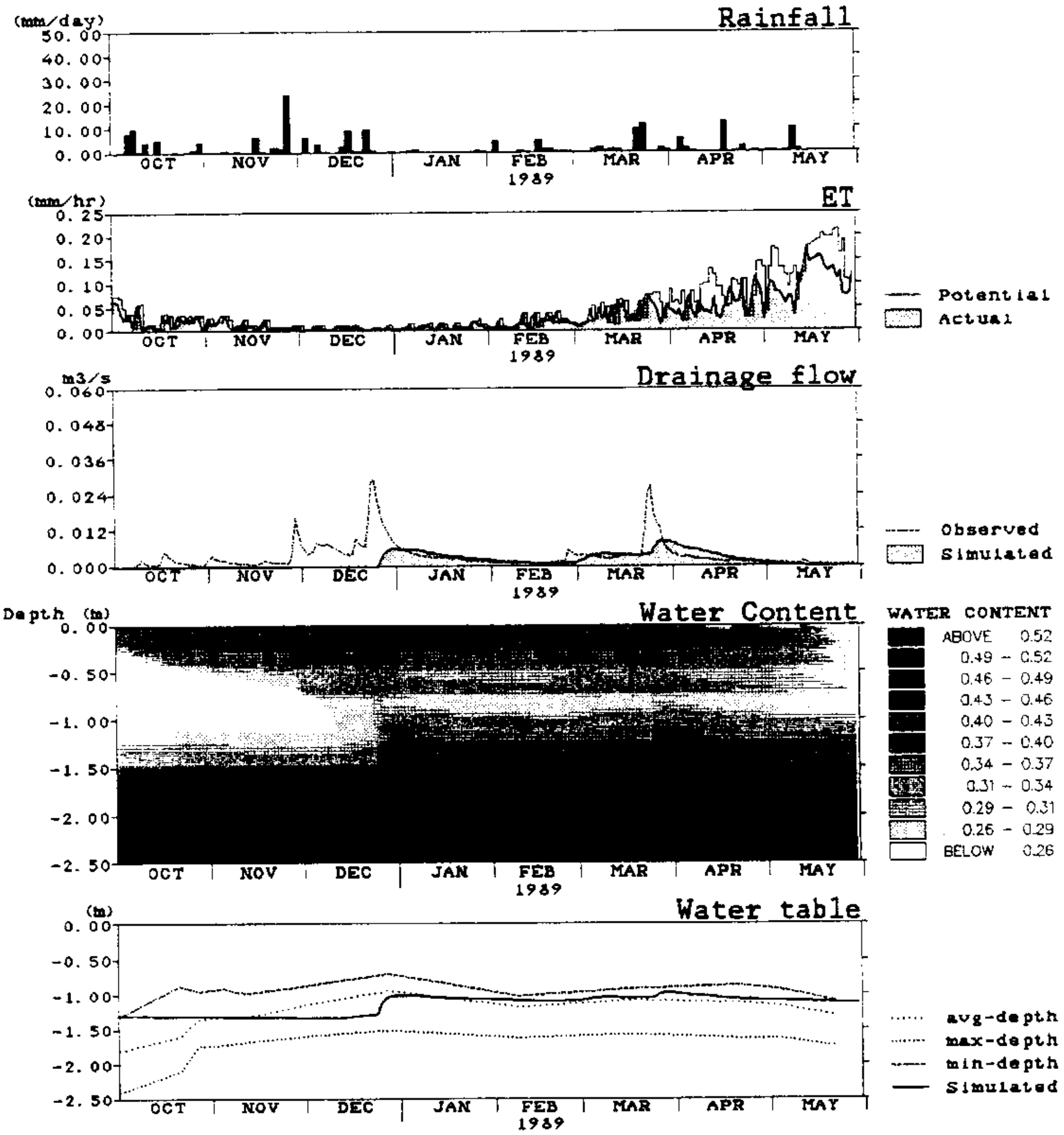


Figure 5

Flow simulation 1a, catchment 2, 1987-88.
(Retention data 1408, bypass ratio $f_b = 0$).



<u>Figure 5, contd.</u>

Flow simulation 1a, catchment 2, 1988-89.

(Retention data 1408, bypass ratio f_b = 0).

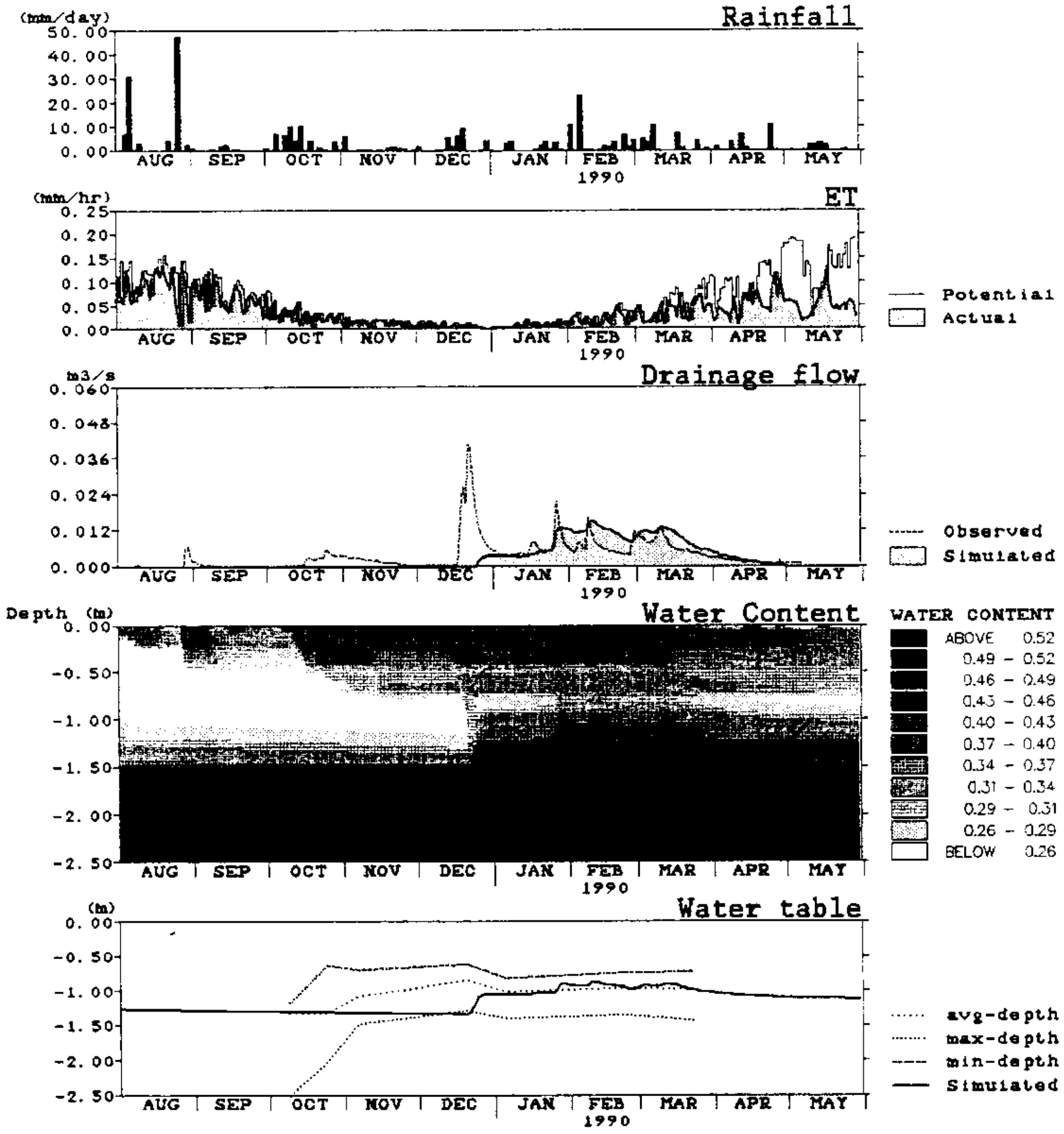


Figure 5, contd.

Flow simulation 1a, catchment 2, 1989-90.

(Retention data 1408, bypass ratio $f_b = 0$).

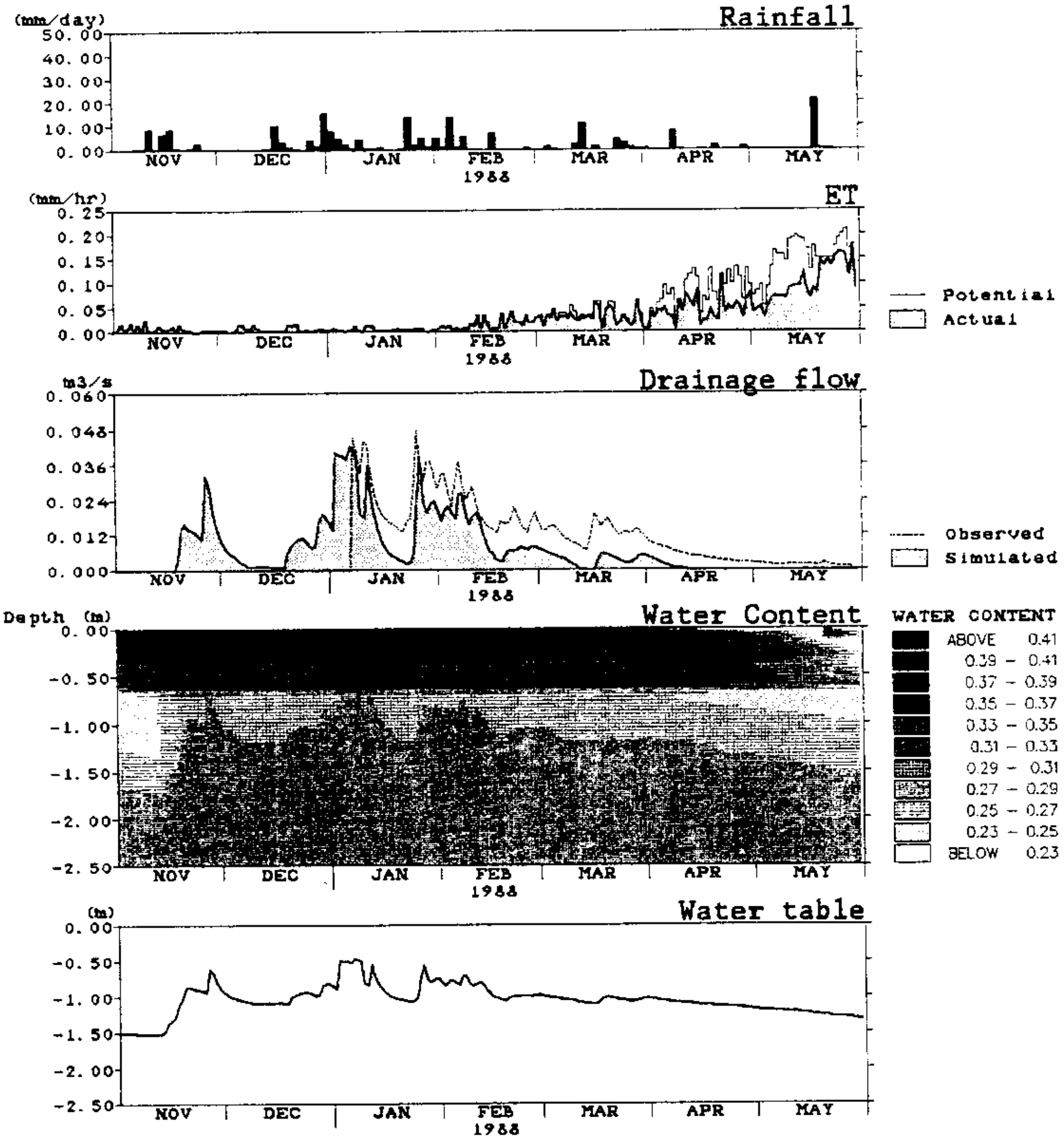


Figure 6

Flow simulation 1b, catchment 2, 1987-88.

(Retention data 1409, bypass ratio $f_b = 0$).

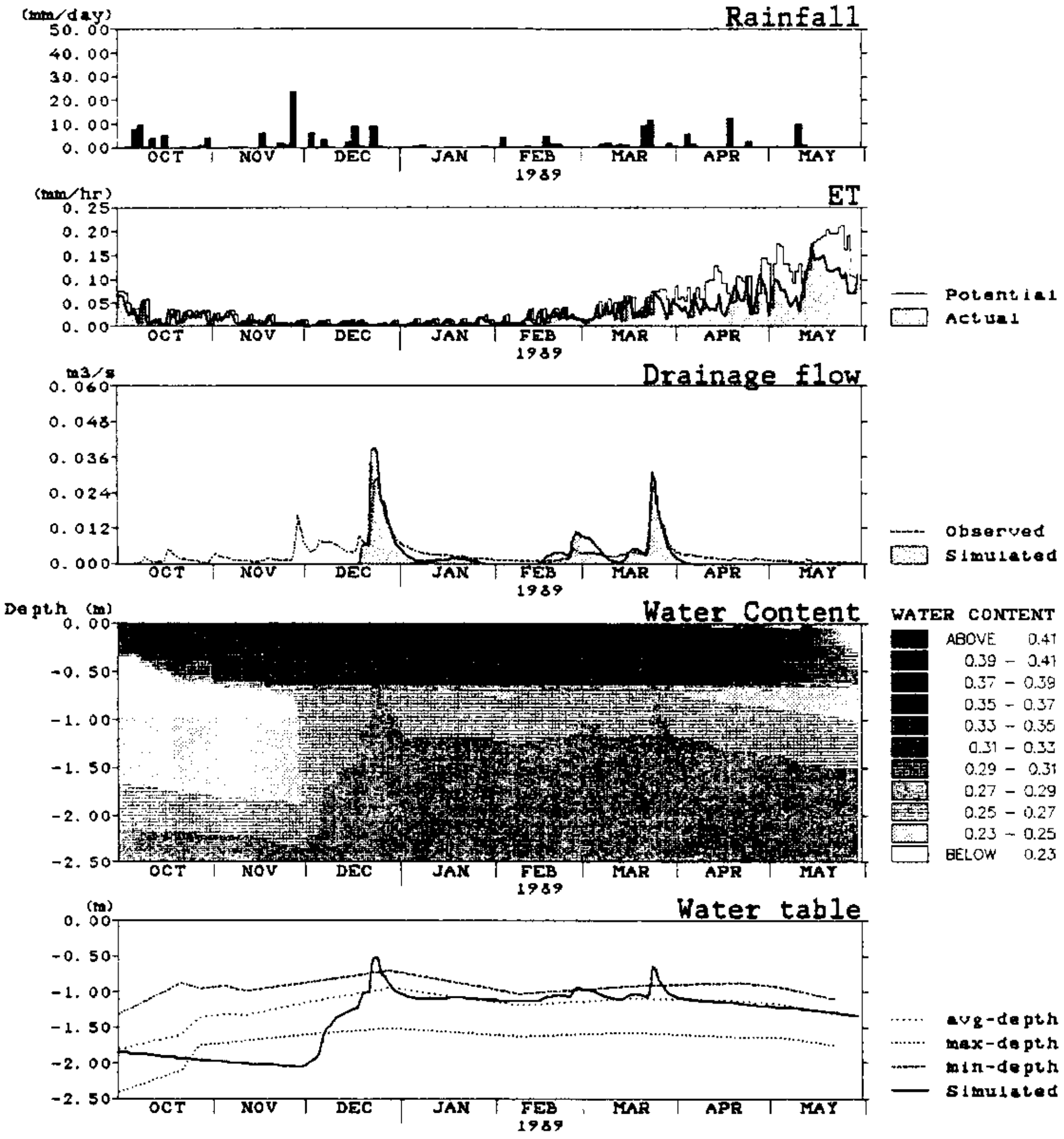


Figure 6, contd.

Flow simulation 1b, catchment 2, 1988-89.
(Retention data 1409, bypass ratio f_b = 0).

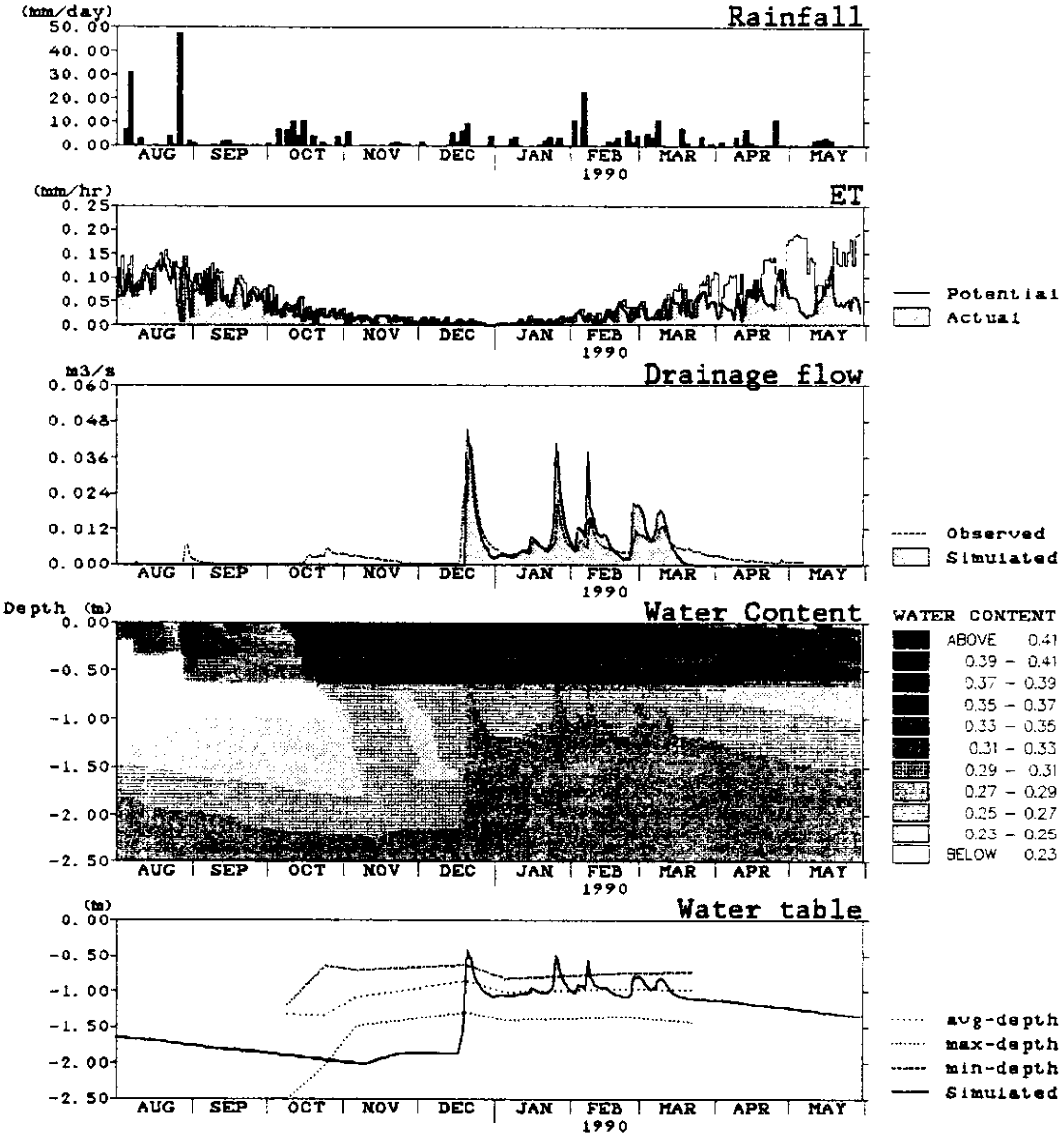


Figure 6, contd.
Flow simulation 1b, catchment 2, 1989-90.
(Retention data 1409, bypass ratio f_b = 0).

is not warranted. Yet, it is evident from the diagrams that the simulated water table position for both soil profiles is reacting too slowly at the onset of the percolation period in the fall. It appears that the infiltrated water percolating out of the root zone should be transmitted more rapidly through the unsaturated zone towards the water table than predicted by the model. Note that the observed and predicted water table levels compare very well in the middle of the recharge period thus justifying the assumption of a drain depth of 1.1 m. By applying the model to drainage catchment 1, the same discrepancies are obtained.

Representatives of retention data

The results indicate that it is not possible to simulate the drainage outflow response on the basis of the soil characteristics from one single profile and by using a traditional one-dimensional Darcy-type flow description. Obviously, this is under the assumption that each of the nine soil profiles considered here represents the hydraulic properties of the unsaturated zone despite the fact that they are actually located outside the two catchments. However, there is no reason to believe that this should not be the case, because no clear trends in the structure of the glacial deposits have been identified.

It should also be emphasized that the conclusions suggested by the analysis are also under the assumption that the hydraulic conductivity function applied in the simulations represents reality. No measurements are available to confirm this function, and it has therefore been estimated by using a calibration procedure developed by Jensen and Refsgaard (1989). However, we expect that this procedure is equally applicable to the soil types and flow conditions prevailing at the present field sites.

Bypass flow included in the simulations

An attempt has been made to improve the model simulations by allowing bypass to occur using the simple model approach described previously. Using a bypassing ratio f_b of 50%, the simulation results shown in Figs. 7 and 8 are based on soil profiles 1408 and 1409, respectively. As it appears from the figures, the model now generates drainage flow much earlier in the season and in fact partly captures the early flow observed in the period August-November. However, during the main recharge period starting in December and ending in April the simulation has not improved for any of the profiles, on the contrary some of the peaks are described less accurately. The earlier generation of drainage flow is also reflected in a higher water table earlier in the season in comparison to the simulation where bypass flow is not considered.

7.2 Simulation case 2

Two sets of retention data included

The retention curves used in the previous two cases are measured on soil samples collected close to both drainage catchments (Fig. 1), and it therefore seems reasonable to consider both in the simulation. Fig. 9 shows the observed and simulated outflow response when the two retention curves are included on the basis of an equal representation. In this case bypass flow is not considered.

Obviously, the simulation is a combination of the results shown in Figs. 5 and 6 and therefore includes the merits of both including the long recession generated by profile 1408 and the short range high outflows generated by profile 1409.

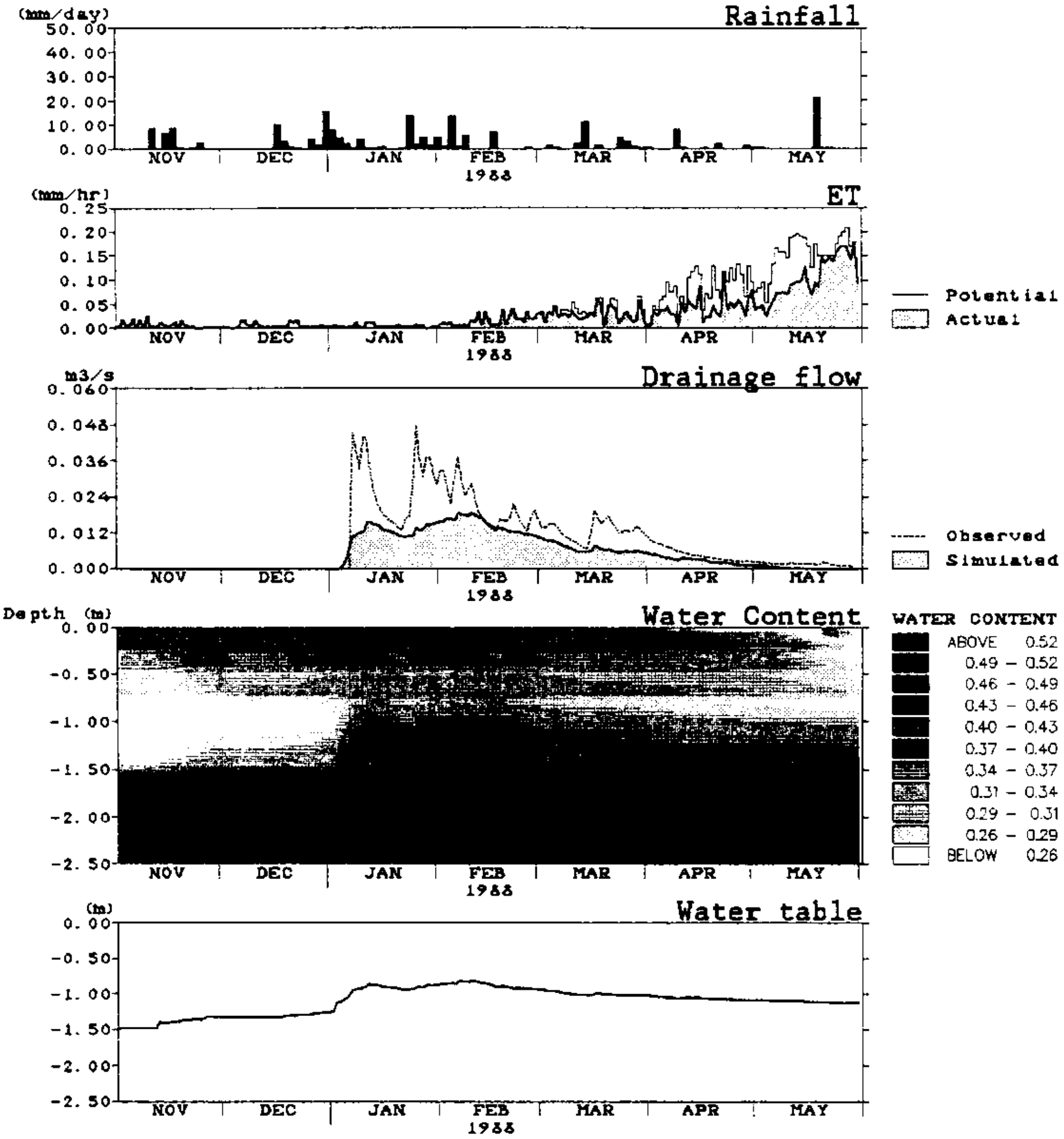


Figure 7

Flow simulation 1c, catchment 2, 1987-88.
(Retention data 1408, bypass ratio f_b = 50%).

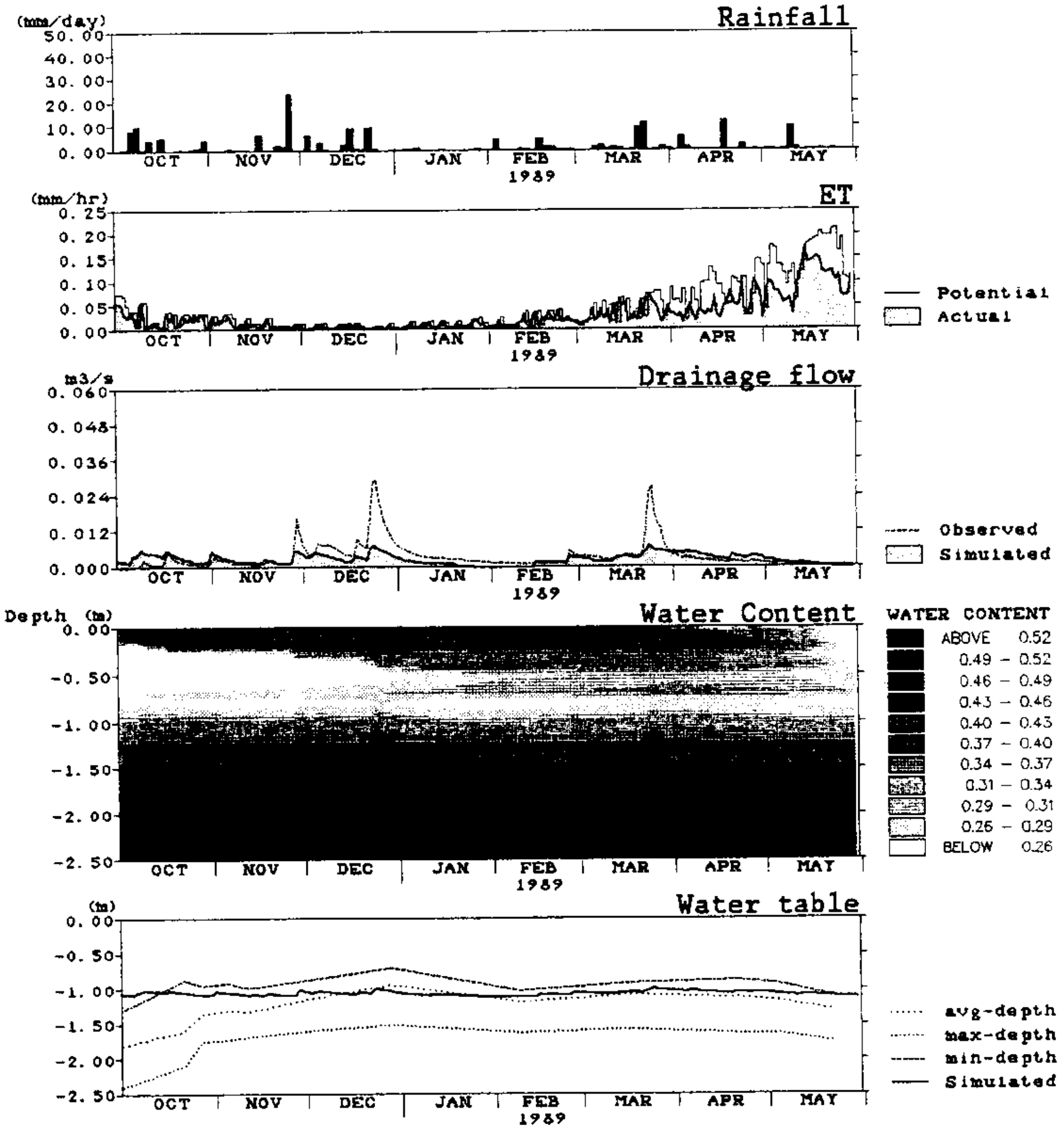


Figure 7, contd.

Flow simulation 1c, catchment 2, 1988-89.
(Retention data 1408, bypass ratio f_b = 50%).

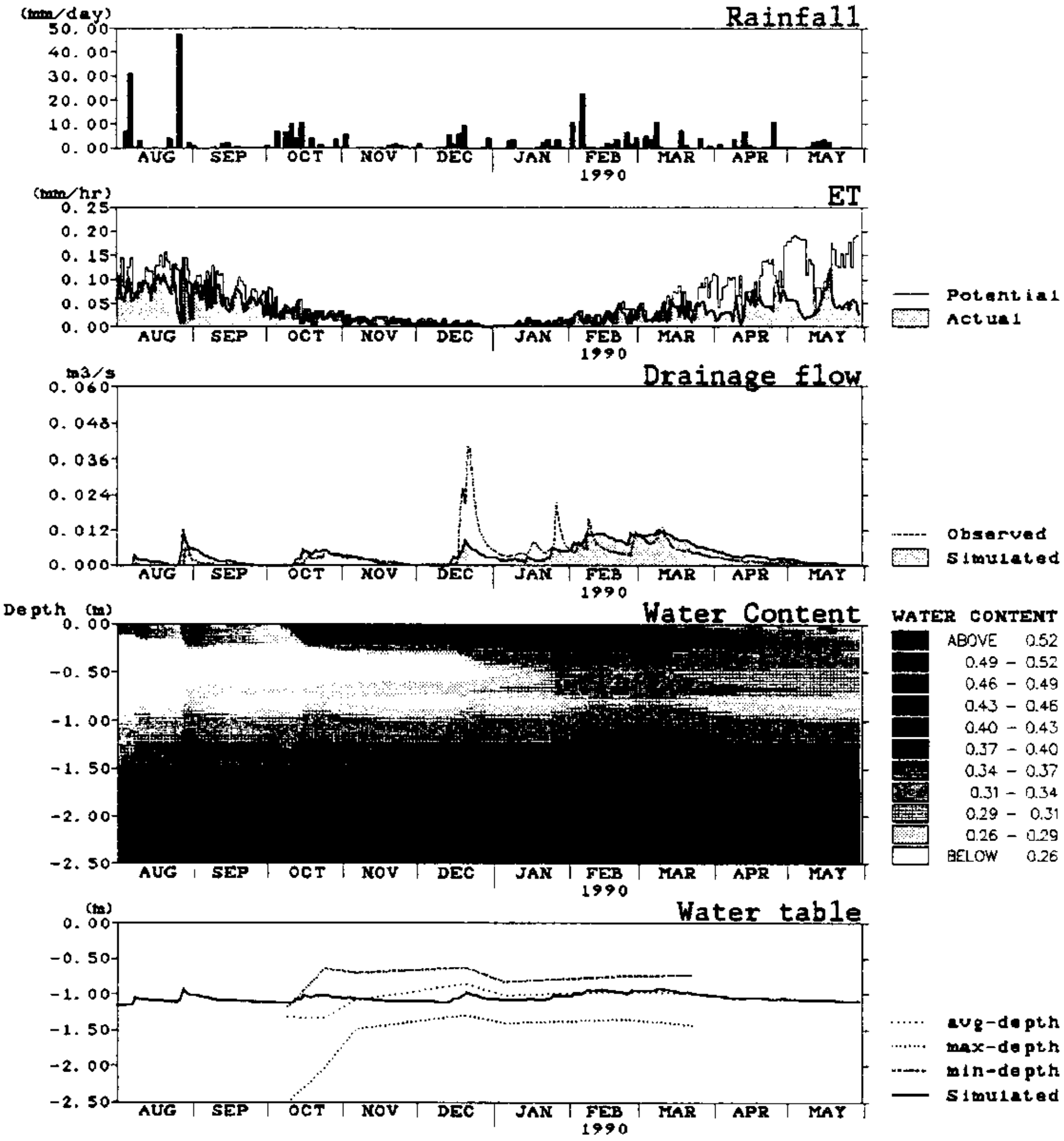


Figure 7, contd.

Flow simulation 1c, catchment 2, 1989-90.

(Retention data 1408, bypass ratio f_b = 50%).

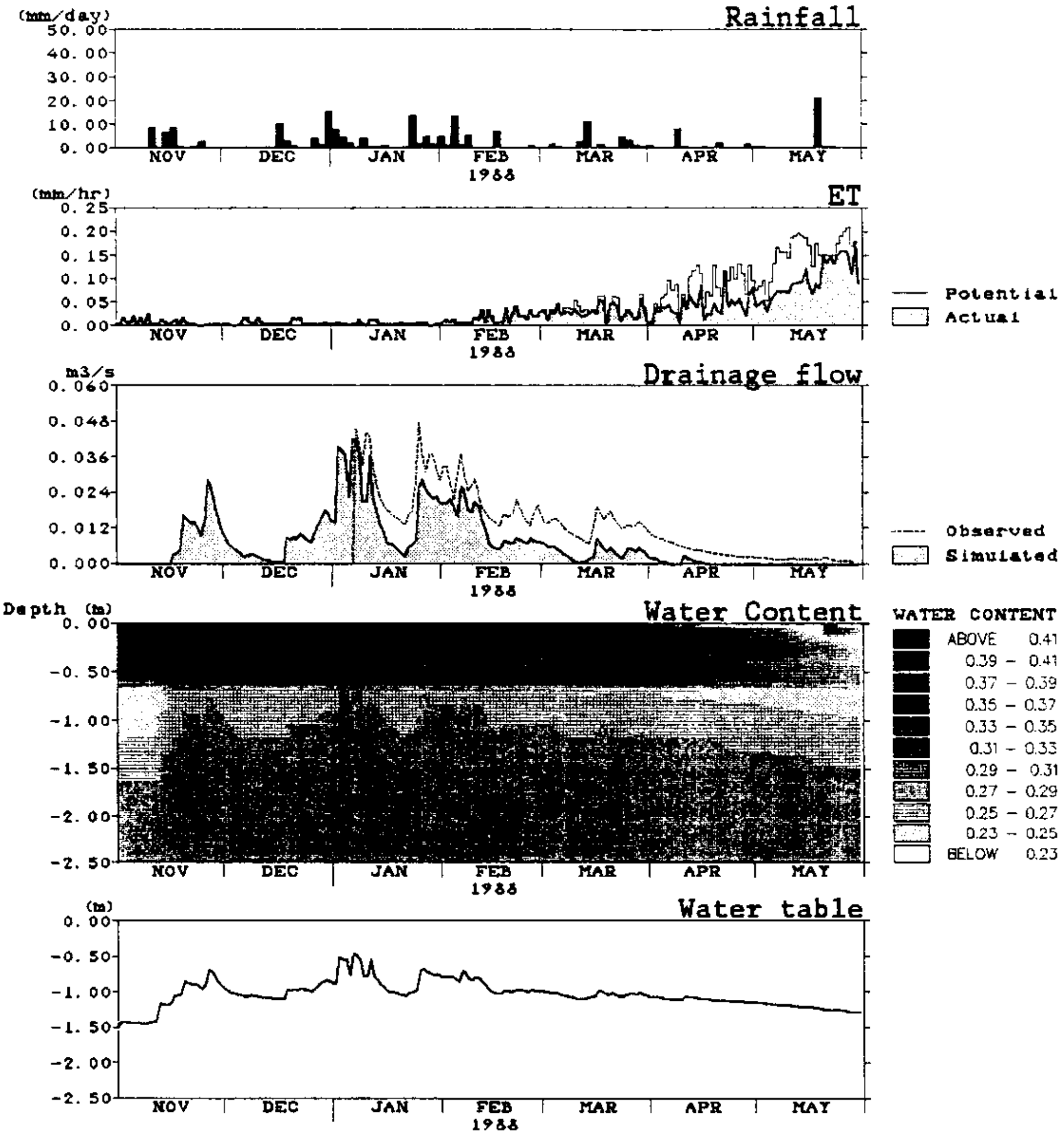


Figure 8

Flow simulation 1d, catchment 2, 1987-88.
(Retention data 1409, bypass ratio f_b = 50%).

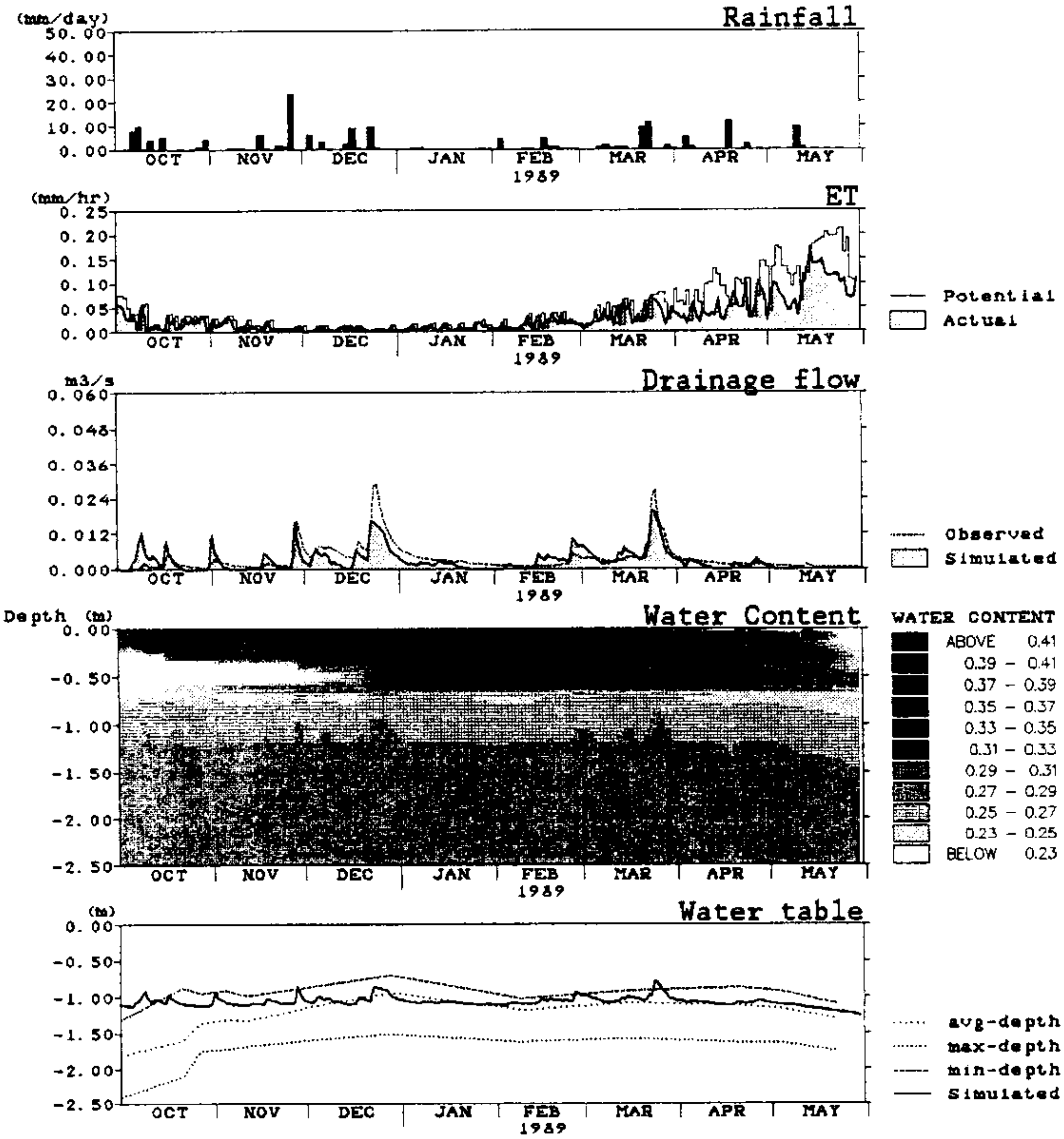


Figure 8, contd.

Flow simulation 1d, catchment 2, 1988-89.

(Retention data 1409, bypass ratio f_b = 50%).

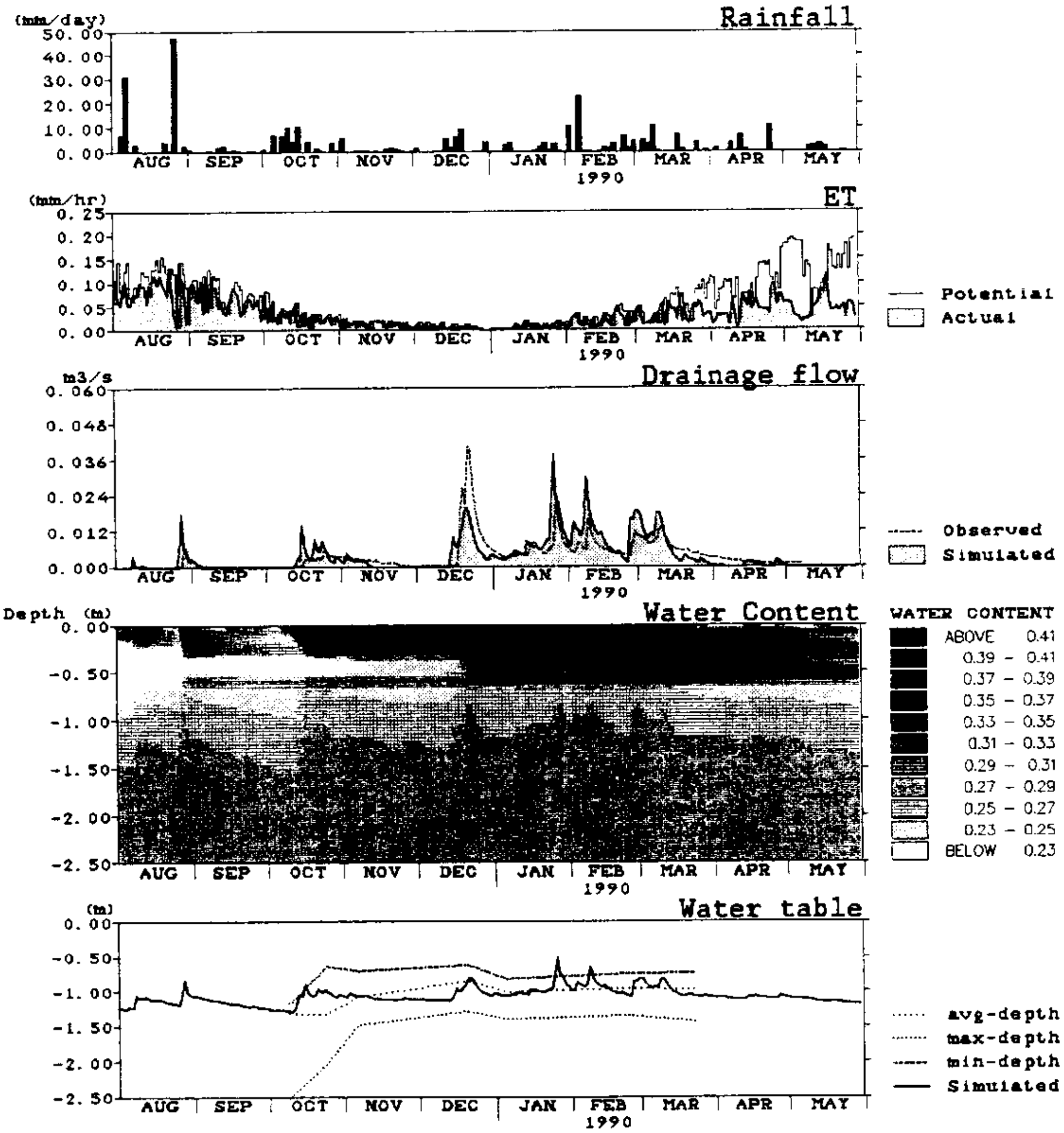


Figure 8, contd.

Flow simulation 1d, catchment 2, 1989-1990.

(Retention data 1409, bypass ratio f_b = 50%).

However, the highest peaks of the 1989-90 season are not described very accurately, and the early-season flow events are still not simulated, as could be expected. Note that the drainage flow of the first three months of 1988 is significantly underestimated. We believe that this discrepancy is related to deficiencies in either the rainfall or the discharge records. By accumulating over the first three months a total discharge of 272 mm is reported, while only 230 mm of rainfall is observed. Furthermore the potential evapotranspiration is estimated to 41 mm during the same period, where no significant storage changes in the unsaturated zone occur. Hence a water balance problem is present.

Bypass flow included

In this case a two-domain model approach is also introduced by specifying a bypass ratio of 50%, Fig. 10. As shown by the figure a better simulation is obtained for the early flow events, and in general the simulation is better than any of those shown in Figs. 7 and 8. Still the highest peaks are not described satisfactorily.

In Fig. 11 the same modelling approach as above is applied to drainage catchment 1 including the hydraulic properties from the two soil profiles. A simulation of the same quality is obtained for this similar size catchment although the highest discharge event is considerably underestimated.

7.3 Simulation case 3

Nine sets of retention data included

This simulation series is produced under the assumption that all nine soil profiles from which retention information is available are equally represented within the two drainage catchments.

Figs. 12 and 13 show the simulations for the two catchments using a single domain approach, and

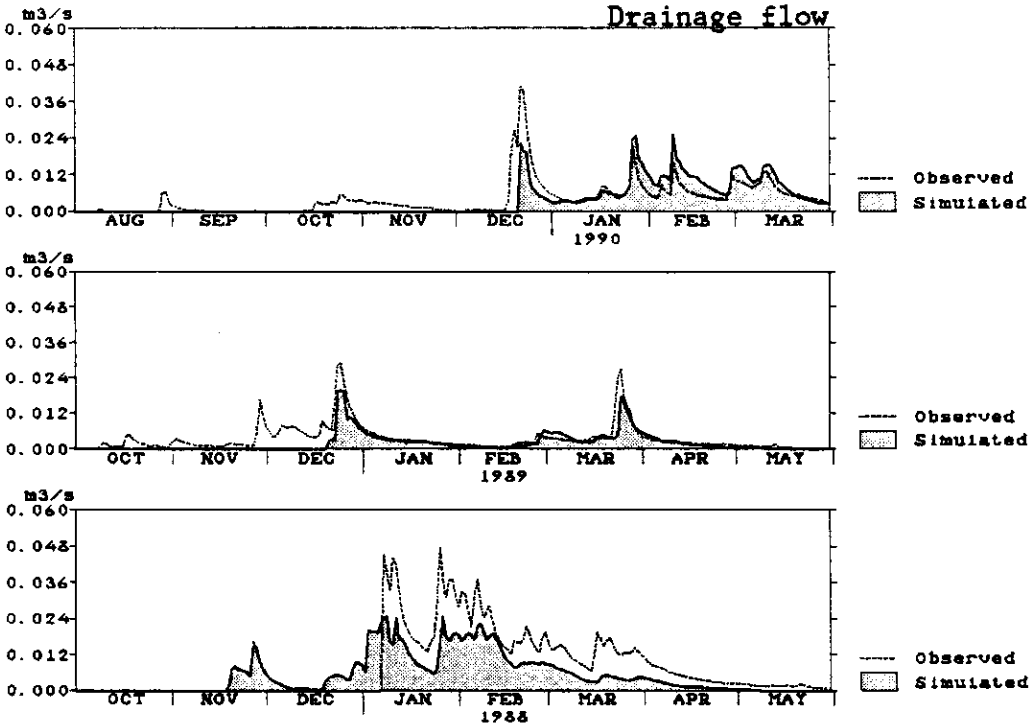


Figure 9

Flow simulation 2a, catchment 2.

(Retention data 1408 and 1409, bypass ratio $f_b = 0$).

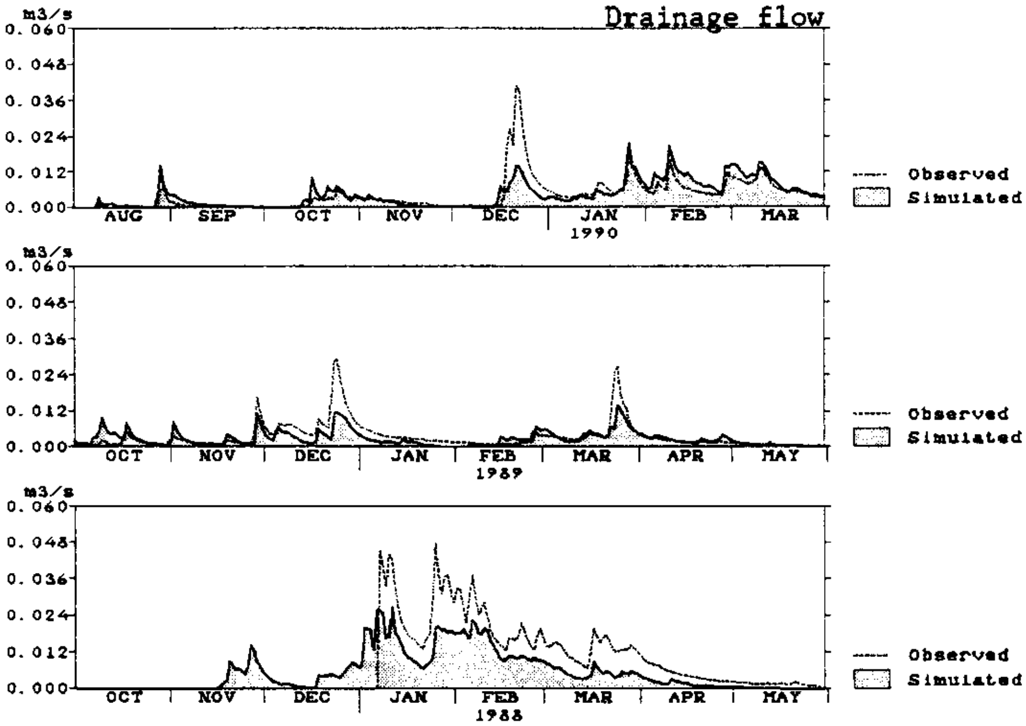
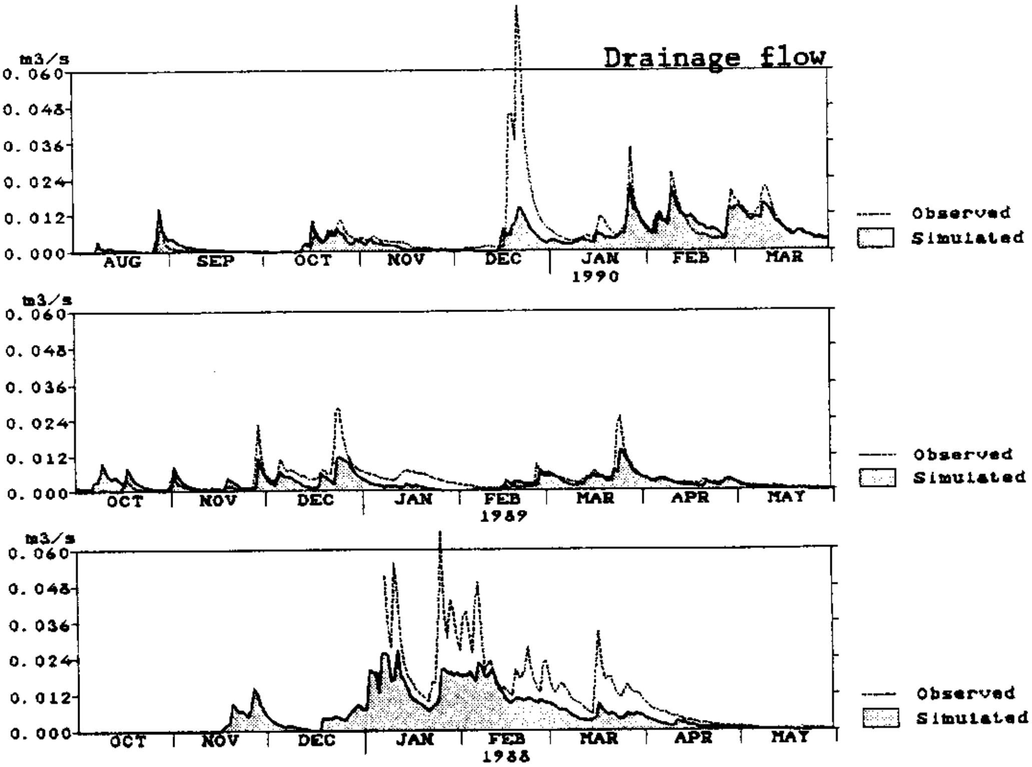


Figure 10

Flow simulation 2g, catchment 2.

(Retention data 1408 and 1409, bypass ratio f_b = 50%).



<u>Figure 11</u>

Flow simulation 2c, catchment 1.

(Retention data 1408 and 1409, bypass ratio f_b = 50%).

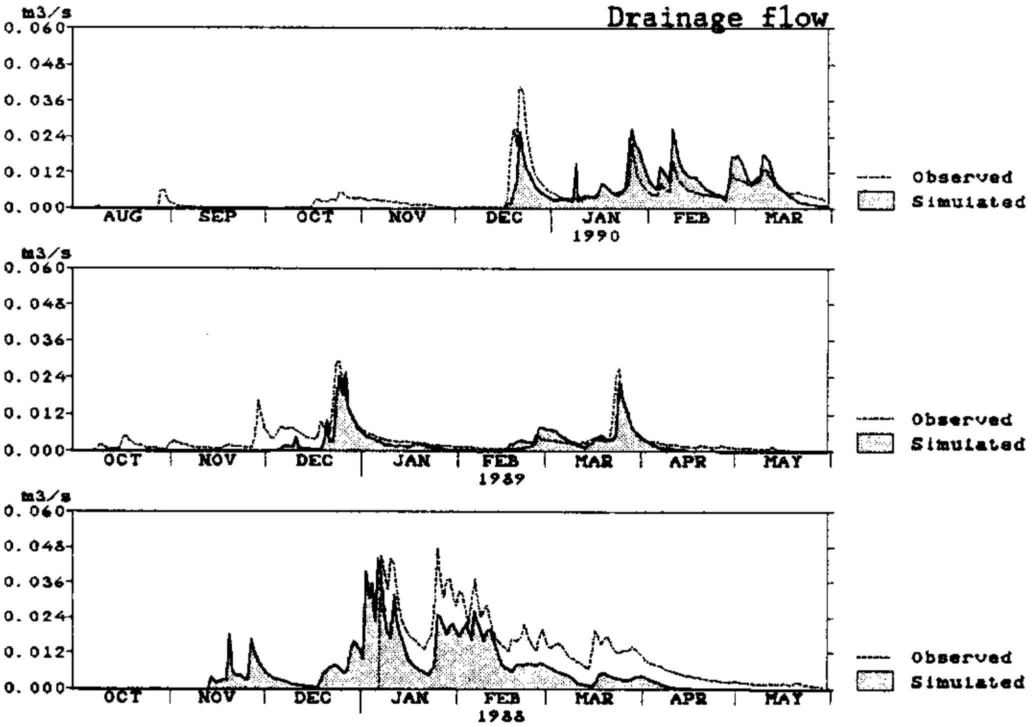
some improvements particularly in the central part of the outflow season are obtained in comparison to the results based on only two retention curves. The analysis therefore suggests that the spatial variability of the soil properties must be considered in order to accurately describe the large-scale outflow from the unsaturated zone.

Bypass flow included

Although the full range of the field-documented variability in soil properties has been included in the model, the early discharge events are not described satisfactorily. Introducing the two-domain description and allowing for bypass flow by specifying a bypass ratio of 50%, the simulation results shown in Figs. 14 and 15 for the two catchments are obtained. As it appears from the figures, the simulations have improved considerably both with respect to the problem discussed above, but the peak flows are also better described except for the highest peak of catchment 1. Note that the 1988 drainage season should not be included in the evaluation because of the water balance problem discussed before.

Bypass flow as a likely flow mechanism

The sequence of simulation runs demonstrated here clearly demonstrates that bypass flow is a likely flow mechanism in both catchments. Strong evidence of this is also provided by the rainfall events during the summer periods where the drain systems responded very rapidly despite a very dry root zone. However, using a modelling approach based on a simple and empirical description for bypass flow and given the available field data and information, we are not able to provide an in-depth quantification of the bypass mechanism. Other phenomena may also interfere such as a variation in drain depth and water table position over the catchments. If the water table locally reaches the drains, small volumes of drainage outflow may be generated, and



<u>Figure 12</u>

Flow simulation 3a, catchment 2.

(Retention data from nine profiles, bypass ratio $f_b = 0$).

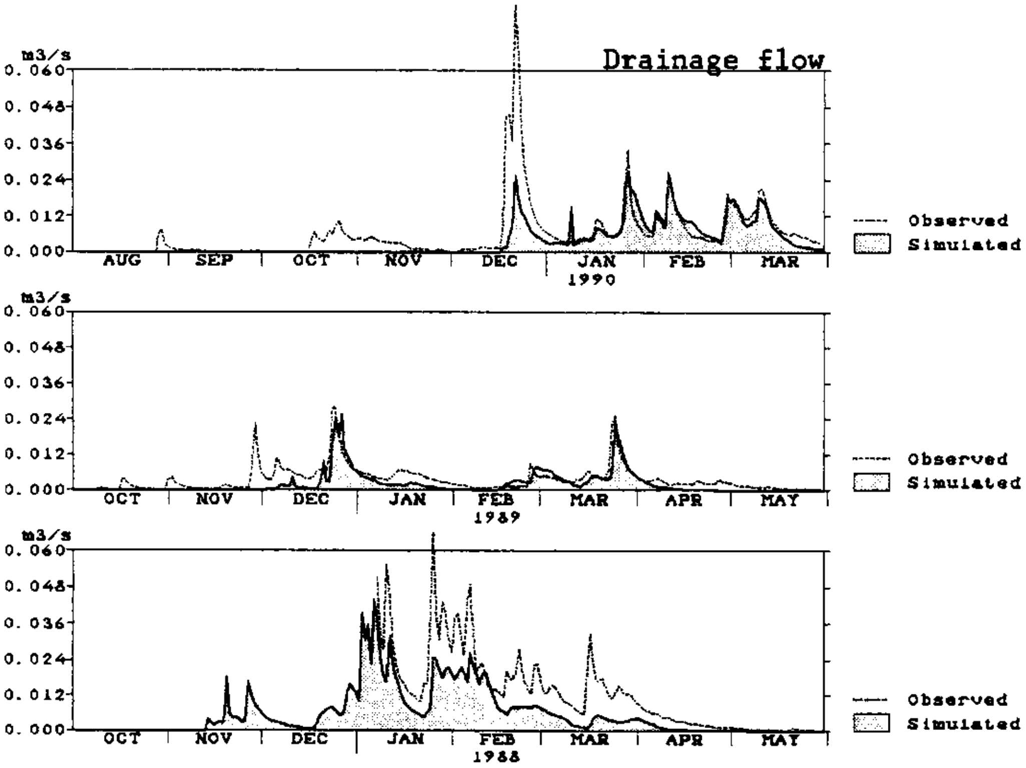


Figure 13

Flow simulation 3g, catchment 1.

(Retention data from nine profiles, bypass ratio $f_b = 0$).

this flow mechanism could in part explain the upstart of the drainage flow. Although flow mechanisms other than bypass flow may contribute to the simulation problems encountered when using a traditional Darcy-type model approach, our analysis of the field behaviour strongly indicates that bypass flow contributes significantly to the flow patterns.

Tracer study required

In order to analyse the contributions from the various flow mechanisms in more detail a labelling of the water particles is required in order to examine the pathways. This can be accomplished by adding a tracer to the system and subsequently measuring for tracer concentrations within and at the outlet of the system, see e.g. Villholth et al. (1990).

A bypass ratio of 50% in this study may seem high, although ratios in that order have been rapported elsewhere, see e.g. Van Stiphout et al. (1987) and Kneale and White (1984). Similarly, Bronswijk (1988) calculated that in one year bypass flow amounted to 27% of the total rainfall, and in separate showers up to 78% of rainfall was interpreted as bypass flow.

If bypass flow as suggested is responsible for a significant part of the recharge, there is a risk that a good part of readily soluble nitrate in the soil profile or, alternatively, fertilizer or manure applied prior to a rainfall event, may be leached to the drains quickly. A secondary effect of bypass flow is the reduction of evapotranspiration, primarily plant uptake and transpiration, and overland flow.

On the basis of the present analysis it is not possible to quantify the increased leaching risk of nitrate, because the model is too simplified, and it does not treat the complicated exchange

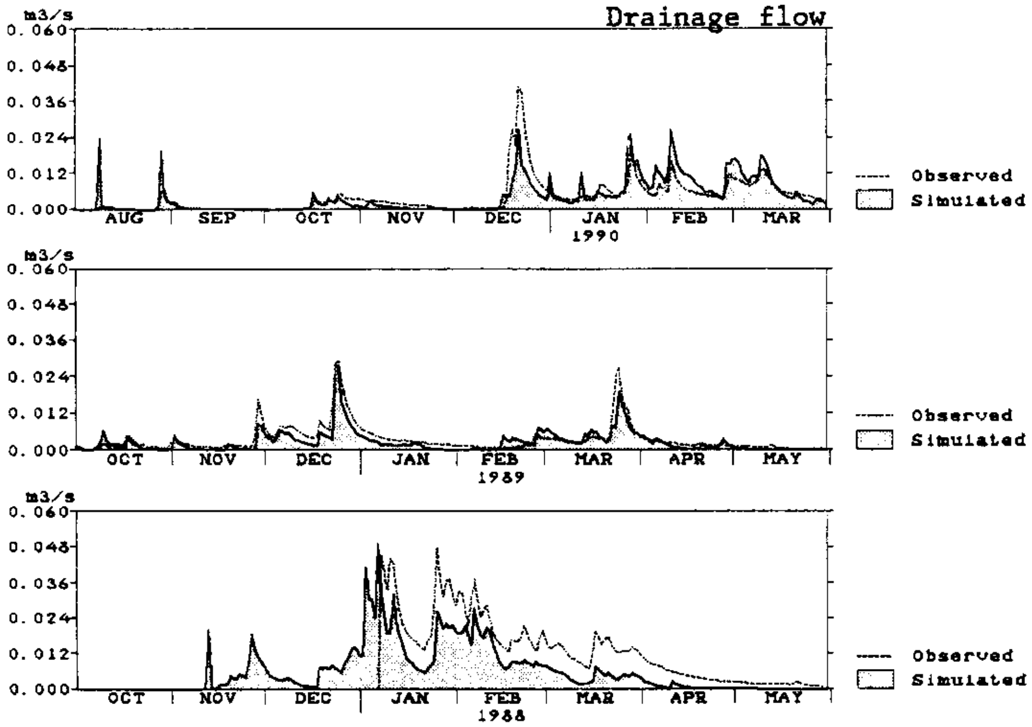


Figure 14

Flow simulation 3c, catchment 2.
(Retention data from nine profiles, bypass ratio f_b = 50%).

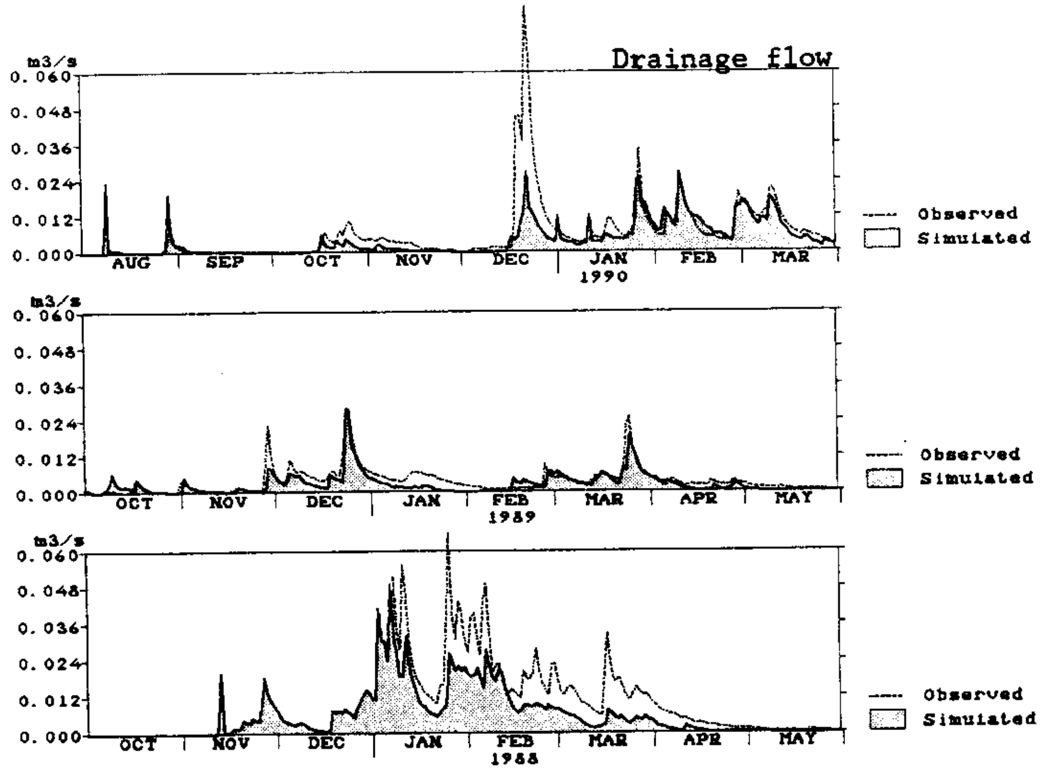


Figure 15

Flow simulation 3d, catchment 1

(Retention data from nine profiles, bypass ratio f_b = 50%).

processes taking place between preferential pathways and the soil matrix. More detailed field investigations including application of tracers are required to pursue this problem.

8. Conclusions

The outflows from two drainage catchments within the Syv Creek catchment have been analyzed and interpreted using a one- and two-domain model for unsaturated flow, coupled with simple descriptions for drainage and groundwater flow.

Spatial variability

Retention characteristics have been obtained from nine profiles in total within the greater Syv creek catchment but outside the two drainage areas being investigated. Under the hypothesis that the retention data from these profiles represent the likely soil variability within the two drainage catchments it is demonstrated that the best simulations of the flow during the bulk part of the drainage season are obtained by including all the available retention information. If only the two profiles closest to the drainage catchments are considered, either separately or in combination, a less accurate simulation is obtained. Consideration to the variability of soil properties is therefore important when predicting the outflow from large-scale unsaturated systems. In relation to the leaching problem, the variability is expected to be equally important although it has not been investigated within the context of the present study due to limitations of the available data.

Two-domain model

Despite inclusion of the full field-documented retention variability it was not possible to simulate the early drainage flow events occurring in the months before the drains start flowing continuously. Particularly it was not possible to capture the mid-summer drainage outflow produced in response to rain storms under conditions when the root zone was dried of water contents well below field capacity. This behaviour can be explained by the existence of preferential flow paths in the soil. Using a two-domain flow model for the unsaturated zone in which bypass flow is introduced, it is possible to establish a much closer simulation of the recorded outflow hydrographs, thus supporting the existence of such flow components.

Other flow phenomena

Other phenomena may also contribute to these flow anomalies such as variations of drain and water table depths over the catchments. To investigate and separate the influences of the various phenomena, tracer tests are required.

Leaching risk

The rainfall-discharge observations strongly suggest that bypass flow influences drainage flow production. Although the problem can not be quantified on the basis of the existing data, preferential pathways provide effective shortcuts between water leached from the root zone and surface waters. Hence, there is a risk that a good part of fertilizers or manure applied prior to a rainfall event may be leached directly to surface waters.

Bypass flow is expected to be of importance only in soils with a high clay content.

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Resumé:
Sammenhængen mellem observationer af nedbør og drænafstrømning er analyseret for 2 drænvandsoplande. En tokomponent umættet zonemodel er anvendt til at simulere betydningen af strømning gennem den porøse matrix og makroporer på drænresponset. Rumlig variabilitet i retentionsdata er inkluderet i simuleringerne. Resultaterne viser, at det er vigtigt at medtage både makroporestrømning og jordvariabilitet for at kunne beregne vand og nitrattransport i den umættede zone.

Emneord:
grundvand; nedbør; dræning; afstrømning; jordstruktur; jordbundstyper; hydrologiske modeller; transport

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Drainage Flow Modelling - Syv Field Site

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Abstract:
Records of rainfall-discharge observations in drainage catchments are analyzed by an unsaturated, two-domain model for porous matrix and bypass flow. Spatial variability of retention properties is included in the model simulations in a simple fashion. It is shown that bypass flow and soil variability have a significant effect on the simulated discharge, and both phenomena should be considered when predicting flow and transport of nitrate in soil systems.

Terms:
groundwater; precipitation; drainage; surface runoff; soil structure; soil types; hydrological models; transport

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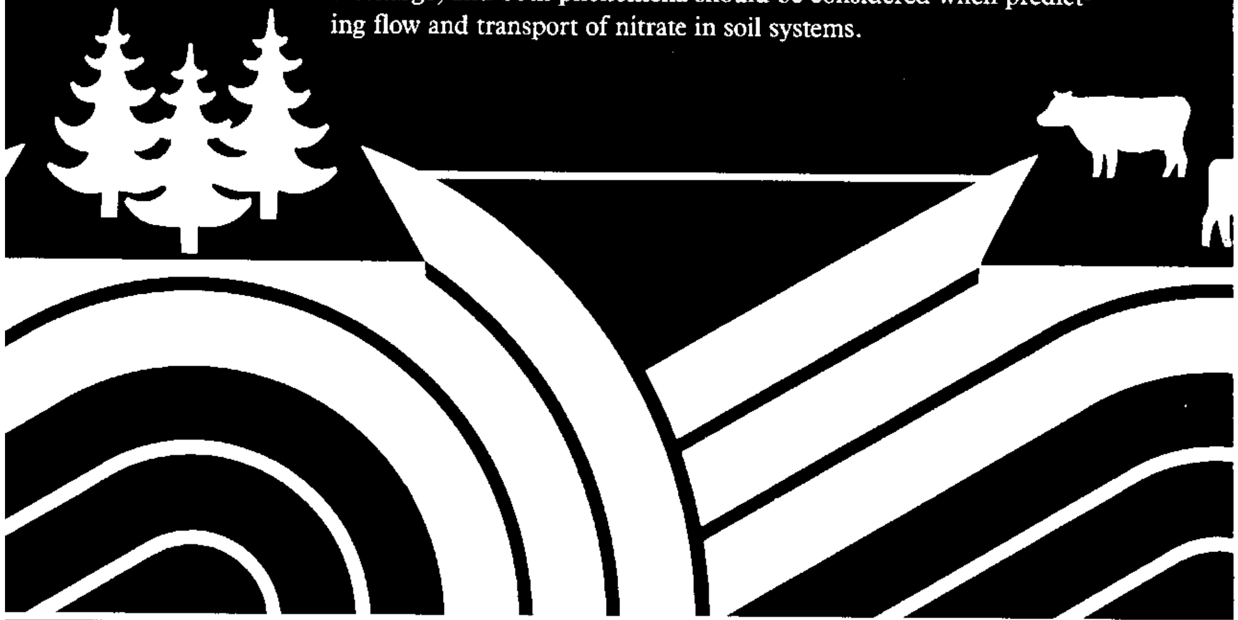

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