Netherlands organization for applied scientific research

International Hydrological Programme of Unesco

Committee of the European Network of Experimental and Representative Basins

# Hydrological research basins and the environment

Proceedings and information No. 44
Verslagen en Mededelingen No. 44

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Hydrological research basins and the environment

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Hydrological Research

Hydrological research basins and the environment: proceedings of the International Conference, 24–28 September 1990 at Wageningen/ (ed. by J.C. Hooghart, C.W.S. Posthumus and P.M.M. Warmerdam) – The Hague: TNO Committee on Hydrological Research. – Illustrations. – (Proceedings and information/TNO Committee on Hydrological Research; no. 44)
With index, ref.
ISBN 90-6743-176-1

Subject heading: hydrology, water management, environment

TNO Committee
on Hydrological
Research

International Hydrological
Programme of Unesco

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Network of Experimental
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Editors
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International Conference
Wageningen, The Netherlands
24–28 September, 1990

**Organized jointly by**

- Agricultural University Wageningen, Department of Hydrology, Soil Physics and Hydraulics
- Rijkswaterstaat, Institute for Inland Water Management and Waste Water Treatment
- TNO Committee on Hydrological Research
- International Agricultural Centre

The Hague 1990

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## PREFACE

The International Conference on Hydrological Research Basins and the Environment, was held at Wageningen from September 24th to 28th. The conference was organized by the Committee of the European Network of Experimental and Representative Basins and the National Committee of the Netherlands for the International Hydrological Programme of Unesco.

Much of our basic knowledge on hydrological processes has come from studies in research basins. These well-instrumented basins have also produced much very suitable data for hydrological investigations an water resources management studies. In recent years the significance of the role of research basins in hydrology has considerably changed. It was found that research basins also constitute an irreplaceable tool for studying anthropogenic effects on water resources and the environment.

Detailed observations and measurements have strongly increased the awareness of the effect of human activities on the quality of the environment and consequently the threat to life. Studying the changes caused by anthropogenic effects is most useful when carried out in well-equipped research basins, supported by basin experiments. Such studies are also a valuable starting point for sound future environmental management.

The main objective of the conference was to bring together scientists involved in hydrological basin research, to stimulate the exchange of information and to encourage international cooperation in research projects.

During the conference the Third General Meeting of the European Network of Experimental and Representative Basins was held. This network of basins, covering nine countries in Europe, organizes periodical meetings and tries to enhance harmonization of observations and methods of analysis, and to implement research projects of common interest.

P.M.M. Warmerdam, Wageningen
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- Agricultural University Wageningen, Department of Hydrology, Soil Physics and Hydraulics (HSH-LUW)
- Rijkswaterstaat, Institute for Inland Water Mangement and Waste Water Treatment (DBW/RIZA)
- TNO Committee on Hydrological Research (CHO-TNO)
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C O N T E N T S

## INTERACTIONS BETWEEN ATMOSPHERE - PLANT - SOIL

**MAN-MADE EFFECTS**

**BIOGEOCHEMICAL CYCLES AND TRANSPORT OF CONTAMINANTS IN GROUNDWATER**

## SURFACE WATER QUALITY

**POSTERS**

# INTERACTIONS BETWEEN ATMOSPHERE - PLANT - SOIL

# EXPERIMENTAL BASINS AND ENVIRONMENTAL MODELS

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Abstract

The relationship of the environmental model to an instrumented basin is one of process simplification, and this has an important bearing on the successful extrapolation of the simulation results to other areas. The two main types of model used to simulate the rainfall/runoff regime are considered, and the flexibility of the lumped conceptual type of model is demonstrated by various examples.

## 1 Introduction

A research basin is set up either as a representative basin for an investigation of the hydrologic cycle, with the long term purpose of extrapolating the results in time and space, or for the study of the changes brought about by anthropogenic effects. Due to the complexity of the processes operating within the catchment system it is impossible to separate the three components of the modelling system: the model algorithm, the observed data to which it is fitted, and the parameter optimisation algorithm (or trial and error study) which aligns the model concepts with the reality of these data. These components of the system interact to produce the simulation and cannot be treated in isolation. The design of a model is dependent on the objective of the simulation and the type and frequency of the data available. The optimisation algorithm forms an indispensable link between the model generated output and the observed data to produce a calibrated model, but the algorithm chosen is often the only one available at the time, and little thought may be given to its suitability for the project. If there is a choice then it may be more a matter of personal preference and experience rather than an operationally based option. The choice also depends on the objective of the simulation and consequently the objective function which is reduced to its lowest value by the algorithm. It is normal to think in terms of the sum of least squares function: the square of residual between observed and predicted flow. However, other variables can be used such as soil moisture deficit, or some estimate of actual evaporation. Least squares is not the only function that can be used: a higher even power can be used for fitting to high flows or a proportional function for base flows.

## 1.1 Models of the catchment system - distributed or lumped?

To design a model of the complete hydrological system of a catchment which accurately reflects the physical and biological processes governing water transfer needs a very detailed knowledge of the system and the way in which these processes interact. Although no model can even begin to simulate all these processes with the heterogeneity of the real world, there would appear to be merit in using the physically based distributed models because of the greater physical relevance of their equations applied to each intersection of a grid over the catchment area. Unfortunately that is exactly what these models are: point estimations of the physical processes. At best it has to be assumed that the parameters governing the processes are smoothly changing between intersections - at worst that they apply to the complete area around, and are discontinuous at the grid mesh boundaries. The question of sensitivity and simplification of physical processes is examined in Gustard et al (1989) in relation to the Hupselse Beek research basin, The Netherlands.

There is also a question of physical scale and grid size; problems which became apparent in the early days of surface trend analysis.

Change the scale of the physical process and vary the grid size and totally different surfaces appear which are related only at the points

common to the generation of each surface. An interesting discussion of discretization and grid scale demonstrating some of the problems which can arise is given by Calver and Wood (1989).
These aspects of a distributed model are such that they can give a fortuitously good prediction or prevent it. Because of the distributed nature of the models it is impossible to relate process parameters at a particular point within the basin occurring at some interval in time previous to the combination of the flows at the outfall, unless there is an areal link which allows the processes within a catchment to be integrated or lumped for a significant area.

Since the distributed model has a 'reality' of its own, the physical equations or sub-models, it is often regarded as mirroring physical reality and offering an insight into the processes involved. Unfortunately, the very process of distribution in fact makes the distributed model a 'lumped' model at the grid scale. A critique examining the problems in making practical hydrological predictions is given by Beven (1989), who pays particular regard to the problems associated with using physical parameters determined at a point in a heterogeneous system and their representation over a grid area.
The necessary initial programme of field calibrations and determinations of physical parameters in the laboratory is likely to take a considerable time before the results can be mounted in a model at the resolution required by a fine mesh grid. Whilst it should be possible in principle to construct a Water Information System on a geographic basis for ease of input of parameters, it appears unlikely that the spatial resolution of such a data base would ever be sufficient for a realistic distributed model. The use of satellite imagery, or aerial photography, is unfortunately not likely to provide a solution to the problem of the areal extent to which particular physical parameters apply - even an apparently simple task such as mapping the distribution of vegetation within a catchment is not easily carried out by these techniques due to problems of albedo and absorption of radiation.
It is suggested that for most purposes the way forward from this type of model is by the use of semi-distributed models using some of the concepts developed in lumped models at the catchment scale. These

lumped models provide areal estimates of the different processes with a relatively simple mathematical representation of their input and output to stores simulating the path of effective rainfall to the catchment outfall. They are highly parameterised models requiring at least a 'water year' of data for calibration, and validation of the fitted model by the usual 'split' record: to fit the simulation and test it with different sequences of input data. In turn, this type of model could well benefit from some distribution of its lumped parameters in time, in particular the runoff delay functions, and space.

These models use the most common simplification of lumping, or spatial averaging, as used in the distributed model at the grid mesh scale, but at the basin or large sub-area scale. The simplifications necessary for small lumped models are discussed by Blackie and Eeles (1985) when applied to the physical structure and processes operating within a basin. In such a system abstraction no account is taken within its boundaries of variations of precipitation, soils, geology or topography. This spatial averaging must occur in all models, including the most complex distributed models, and the only criterion of its success is the achievement of the objective of the simulation. Spatial averaging at this scale requires that the whole system can be represented mathematically using only the dimensions of depth and time. The key factors to the successful application of these models are the quasi-steady state of the catchment system, and a stable spatial distribution of precipitation over the catchment topography; even highly asymmetric patterns of rainfall are acceptable so long as they recur regularly. The apparent stationarity of processes within a catchment system has been questioned using a lumped model to demonstrate the variation with time of actual against simulated flows by Robinson et al (1990).

## 2 Model applications

From the above discussion it would appear that lumped conceptual models would be simple and flexible in use and represent a pragmatic approach to a simulation of catchment data with minimum cost. Although it was originally thought, Abbott et al (1986), that the length of observed data requirements for calibration of these models often prevented their use, the time required for the determination of parameters for a fully distributed model becomes of the same order, but is expensive in terms of field and laboratory work.

## 2.1 Lumped Conceptual Model description

The applications described here are made using a model developed over a number of years from 1969 at the Institute of Hydrology. It has passed through a number of different concepts and modular structures. The basic model has five stores representing the vegetation cover, the soil surface layer, soil profile, groundwater store, and the surface channel store; outputs from the channel store and the groundwater store are each delayed by a period which allows them to be combined as flow from the basin. Similar types of model storage and routing have been widely used in various models. The model concepts are discussed in detail by Blackie and Eeles (1985) and are only briefly described here.

Evapotranspiration takes place from the vegetation store and the two soil stores by means of multiplier functions applied to Penman Open Water evaporation, but any standard index of evaporation potential can be used - or even pan evaporation data. A cosine reduction function decreases the apparent transpiration by the vegetation from a soil moisture deficit (SMD) which could be considered as the Penman root constant to a deficit which is the 'wilting point'.

A partitioning function splits the 'overflow' from the soil surface store by estimating the rapid response runoff, and the remaining effective rainfall is allowed to percolate to the main soil store. The partitioning function has terms which represent the decreasing infiltration with SMD and the increased runoff caused by rainfall intensity. Surface runoff is then routed through a non-linear store representing the channel flow, and delayed before it combines with the groundwater flow from the basin.

Percolation from the soil store to groundwater is estimated by another cosine reduction function which allows some transfer of water at SMDs below field capacity for the soil type. The observed baseflow recession curve can be used to establish the parameters in the non-linear release function, or they can be estimated by the optimisation algorithm. In the latter case errors stemming from the modular structure of the model may affect these values considerably.

To optimise the parameter vector of the model two algorithms are used: a variation of the Rosenbrock (1960) algorithm with rotation of the parameter axes to establish the order of parameters within the modular structure, and that by Nelder and Mead (1965), to determine the fine structure of the vector components by use of a simplex search of the objective function hyperspace.

## 2.2 Applications - Extension of historic flow records

The concepts of the lumped model have previously been considered as adequate only for small catchments with homogeneous vegetation, soils and geology, but their application has been successfully made to complex regions of the order of 2,000 $km^2$ such as the Upper Thames river with four major tributaries. This work was undertaken by the Institute of Hydrology for the U.K. Government Department of the Environment to extend the available data backwards in time from October 1951 to January 1882 in order to provide a long run of data for water resource planning.

The calibration of the model was made using data for the period from June 1973 to December 1976 and achieved a daily correlation with the observed flows of 97.6% (monthly 99.1%), and a total error in flow of 0.5%. The data for this period were chosen as being considered to be more reliable. The period back to 1951 was used to validate the calibrated model and this produced a daily correlation of 92.4% (monthly 96.3%) and a total volume error of 6.6%.

This error in volume prompted a further comparison of the simulated and observed data for this period, and it was found that the error was largely made up by overprediction of the high flows during winter months. Investigation of this volume error identified a problem with the gauge positioning prior to 1963, in that part of the flow was bypassing the gauge at flows exceeding 50 cumecs.

The model was therefore considered as successfully calibrated and the simulated flows from 1882 compared well with the observed flows from the whole of the Thames basin.

## 2.3 Applications - Changes of land use

The variation of flows due to changes of land use have been simulated for each area affected, and weighting the resultant outputs in time as described in Eeles and Douglas (1990). This provided seven simulations of 53 years of daily data to assess the effects on basin water yield of changes in level of afforestation around an important series of reservoirs in the Elan Valley (185 $km^2$). These simulated data runs were then used as inputs to the Severn/Trent regional resources allocation model to assess the financial and operational results arising from afforestation of the reservoirs' gathering grounds. At 100% forest cover the predicted loss to basin water yield was 38%, while by clear felling the current 2.5% of forest the increase in yield would be just over 1%. For that study the loss functions normally used in the model vegetation components were changed to incorporate the evapotranspiration and interception loss equations of Calder and Newson (1979) for forest and heather cover; the standard grassland and open water components were used to represent the rest of the basin. This brought the dimension of the parametric vector to 35.

Another use for this version of the model was to assess the effect on low flows of afforestation using a model calibrated on the gradual clear felling of a partly forested basin (Gross et al, 1989). This catchment is at Plynlimon in Wales with an area of 3.17 $km^2$. The model was shown to systematically under-predict low flows during the felling, although relative changes in flow regimes were satisfactorily modelled. Subsequently to this work it was found that the datum for the gauging structure was in error by 7 mm due to modifications to the flume at the beginning of the felling period, and that the low flows had in fact been satisfactorily simulated!
As the FREND report noted the "...conceptual modelling studies have shown that land use change is an important influence on flow regimes and have highlighted the need to use models and data from small

research basins to address water resource problems." (Gustard et al, 1989).

## 2.4 HYRROM.

This is an acronym for HYdrological Rainfall/Runoff Model which is basically the model outlined in section 2.1, but with only nine parameters available for change and the rest fixed. The model is available as a software package for mounting on an IBM PC and is beginning to be widely used. It was originally developed as a package for use in the Windward Isles on St. Lucia, but was found to have a much wider application, and has successfully simulated such catchments as the Kenwyn at Truro in the U.K. (area 19 $km^2$) over the extreme drought and subsequent recharge of 1976. It can also be used with monthly data inputs with the usual restrictions applicable to any monthly model: it simulates observed data well when the inputs are changing slowly, but when rapidly changing the total volume is predicted well, but not the invidual months.

## 3 Concluding discussion.

Two main types of rainfall/runoff modelling have been developed - each with their strengths and weaknesses for achieving the objective of a particular simulation. The main limitation with lumped conceptual models is the need for observed data against which to calibrate the model, since only very general relations exist between the parameter values of the different stores and the physical properties which they purport to represent.

The distributed model was thought initially to have the ability to overcome this problem because of its greater physical relevance removing the need for series of observed data, but it has problems with the lack of data on distributed parameters, grid scale and discretization, and the initialisation of store contents. Although in theory these problems can be overcome, in general they can seriously affect the fit of the model to any observed data.

However, the flexibility of the conceptual model has been widely demonstrated in the simulation of the rainfall/runoff regime. It has found applications in estimating the effects of land use changes and in an hourly model has been used to examine anthropogenic changes. The ability of the model to generate long time series of data if the precipitation input is available has been used in the planning of water resources and estimating the consequent costs of water engineering works.

Extreme events can be input to assess the probability of flooding and the effects of a prolonged drought on the recession flow can be estimated. It can also be used for experimental basins in which flow distributions are altering due to anthropogenic changes, in order to separate the effects of climatic variability and human influences.

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# IMPORTANCE OF THE EXPERIMENTAL BASIN FOR CONCEPTUAL DISTRIBUTED MODELS

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Abstract

Flow measurements at different scales, isotopic tracing and water table level monitoring enable us a better understanding of runoff generation mechanisms and provides reliable informations in evaluating the effects of land use changes. For different antecedent soil moisture conditions, various storm frequencies and some specific land uses, several flow processes have been observed on some elementary areas of the Haute Menthue watershed. The overall behaviour of the watershed at the outlet indicates that some of the response characteristics, identified at a small scale are hidden in an average hydrograph. This paper also advocates the need and usefulness of field investigations for the application of physically based models.

## 1 Introduction

The relatively recent development of physically based models, can hopefully provide engineers with improved approaches to assess the effects of land use changes. However, validation of physically based model is questionable since a large number of parameters can not be derived from outlet hydrographs alone and simple watershed characteristics. The question is: should these models be simplified or is it worthwhile to gather the data required ? Anyhow, a better understanding of the hydrologic behaviour of the catchment is necessary.

The research watershed of the Haute Menthue has been equiped for this purpose. For the time being, the study emphasizes on flood events.

The watershed and the equipment

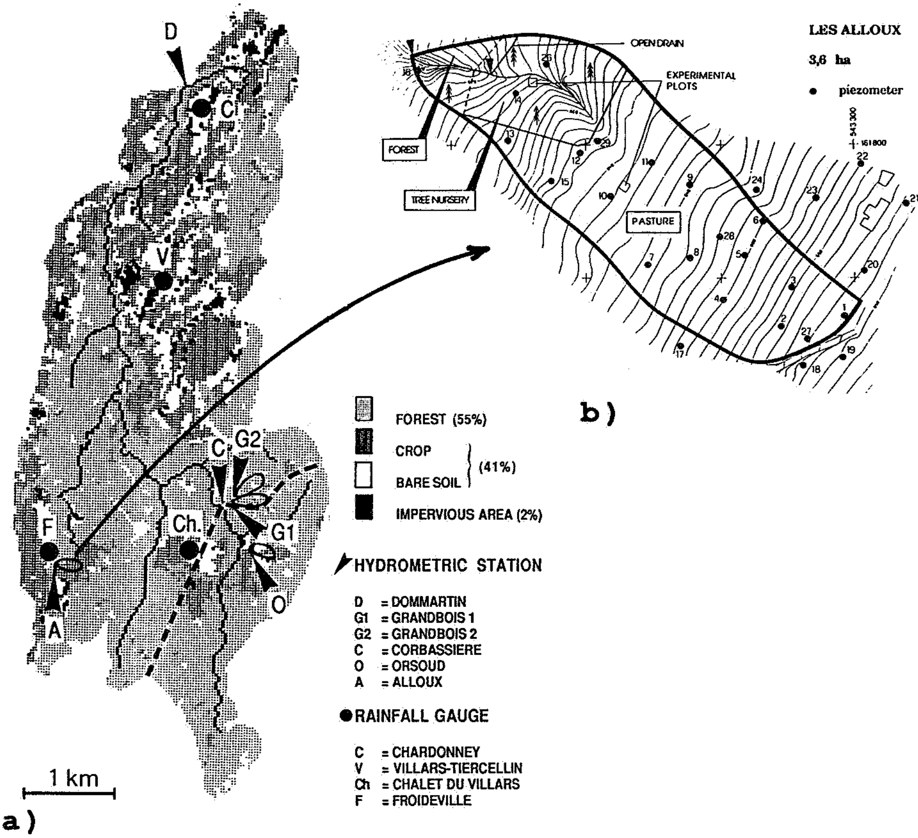


Figure 1. Land use and equipement of research basin, a) Haute Menthue b) Alloux

The Haute Menthue watershed (12,5 km$^2$) is located on the Swiss Plateau, north of Lausanne. The forest area covers 55% of the total area and stretches on the upper part of the catchment and along the streams. The rest of the area is essentially rural with mixed farming and pasture (figure 1a). The rocky substratum is entirely molassic. The material, predominantly sand and silstones, generate a smooth relief, excepting the ravines where the erosion is recent and fast. Water never penetrates deeply into this rock layer of 1 to 2 meters thick. Its degradation is the origin of a highly permeable sandy layer of 50 cm. The presence of this layer explains the large number of little sources that generate an expanded hydrographic network. Soils are silts that become more sandy with depth. The average hydraulic conductivity is around 1m/day, but several traces of hydromorphism have been observed.

Flows at the outlet are recorded from 1975 by the National Hydrological and Geological Service. Four rainfall gauges were installed in 1987 throughout the Haute Menthue catchment.The study of flood generation mechanisms is based on the monitoring of four small sub-areas (few hectares) of order 1 according to geomorphologic homogeneity criteria (slope, area, exposure). However, land uses are different, since forest ("Grandbois 1 and 2"), pasture ("Alloux") and farming ("Orsoud") are predominant in each catchment. A network of piezometers completes the experimental setup. Pedologic and topographic characteristics have been determined with care. One of the four elementary areas (Alloux, figure 1b) has been monitored more extensively and is considered as a comparative reference. Isotope $O_{18}$ tracing was used. Two experimental plots are monitored with probe tubes to record water content. Devices which continously record phreatic levels, tensiometers and samplers in the soil are operational. Flows are also recorded at the oulet of a 2 $km^2$ sub-area (80% of wooded area) located in the upper part of the Haute Menthue watershed.

## 2 Flood processes

Since 1988 when all measurements started, only a few significant events have been recorded, the year of 1989 has been particularly dry. Fifteen hydrographs from the different catchments with homogenous rainfalls higher than ten millimeters have been selected for the purpose of this study. Results will have to be confirmed with the analysis of future measurements, especially rare events. The comparison between hydrographs from the different elementary areas shows that the responses are quiet different and that no correlation exists between catchments, excepting the two forested areas for which the determination coefficient of the linear regression between peak or base flows is higher than 95%.

The two rainfalls of September 9th and October 10th 1988 (figure. 2a and b) have comparable intensities and generated peak flows at the Haute Menthue outlet with return periods slightly higher than one year. The Alloux catchment reacts in a different way. The response time of the first event is less than 10 minutes (figure 2a). This hydrograph includes mainly water already present in the soil before the event ("old water") representing 100% of the first peak and 60% of the second. Subsurface flow is therefore predominant for this event that occured with dry antecedent soil moisture conditions. At the end of the rainfall, the water table level only reaches the surface at a few points in an area that is not directly connected to the stream. The runoff coefficient is equal to 2% and only the areas along the stream borders contribute to runoff.

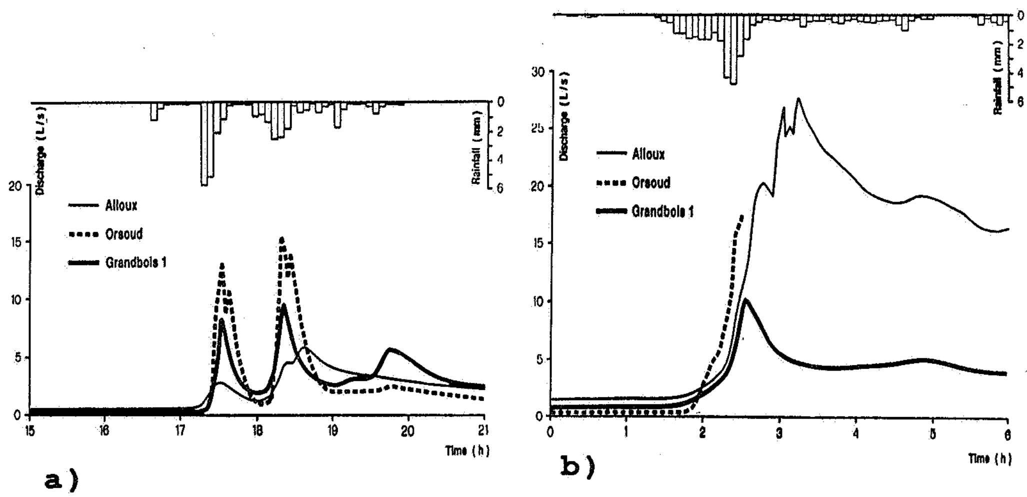


Figure 2. Hydrographs recorded on the elementary watersheds
a) 09/09/1988 b) 10/10/1988. Rainfall mesured at Froideville

The October event (figure. 2b) occurs with saturated antecedent soil moisture conditions after a rainy week. The water table quickly reaches the surface level and spreads over most of the watershed. The hydrograph has a higher response time than that of September (some 30 to 40 minutes), because contributing surface is larger (runoff coefficient = 25%). The saturated overland flow combined with return flow, is predominant for this second event and the subsurface flow is negligeable with respect to the flood flow.

Taking into account the spatial variability of the september rainfall, it appears that for the other elementary areas, the same process dominates (figure 2a and b). Nevertheless, bare soils of the cultivated watershed (Orsoud) favour excess infiltration overland flow and this process can not be neglected even if it appears to be localised. The october event illustrates the effect of forest on saturation excess overland flow. Hydrographs and water table depths shows that the extent of the saturated areas is limited. Therefore, at this scale, the role of the forest seems to be very important. This behaviour can not be attributed exclusively to the entirely wooded areas, since forest along the borders of the stream has definitively a significant effect on hydrologic response. The elementary cultivated area shows a behaviour similar to that of Alloux at least until the interruption of measurements.

The three most important mechanisms of flood generation can be observed in our watersheds as a function of antecedent soil moisture conditions, storm frequency and soil cover. The sand layer over the impervious substratum favours subsurface flow, while the flat topography and the presence of this low thickness substratum leads to temporary formation of saturated areas. Agricultural intensive practice leaving bare soils during long periods of the year, favours a hortonian type of runoff for high intensity storms.

At a bigger scale, the comparison between flows (from the sample of hydrographs) at the outlet of the 12.5 $km^2$ and 2 $km^2$ subwatersheds seems to indicate that the differences between the elementary watersheds dissappear. Even if respective soil covers are not comparable (55 and 80% of wooded are), flows are highly correlated (determination coef.>95%) and hydrograph shapes are very similar. The hydrographs from these two bigger watersheds hide the effects of land use which were easily perceptible at smaller scales. The existence of a Representative Elementary Area (REA as defined by Wood et al., 1988) could be verified.

## 3 Modeling aspects

The information that has been gathered up to now, even if incomplete, is very helpfull when approaching the modeling phase. For instance, it is justified to doubt about the need of a fine schematisation, especially when the model is calibrated or verified mainly with measurements at the outlet. As shown above, up to a certain area, these hydrographs do not contain a significant amount of informations regarding the spatial variability of the various processes. Simulations with the SHE Model (Abott et al., 1986) were conducted in order to test two levels of detail on the Haute Menthue watershed (25 and 100 grids) (Jordan et al., 1987). In the absence of a better knowledge of the system, increasing the number of grids can only be justified when it is desired to achieve a better representation of the topography and the hydrographic network. The 12.5 ha grid is not small enough to account for the real effect of topography and hydrographic network and when using smaller grids, figure 3 shows that no significant improvement is obtained.

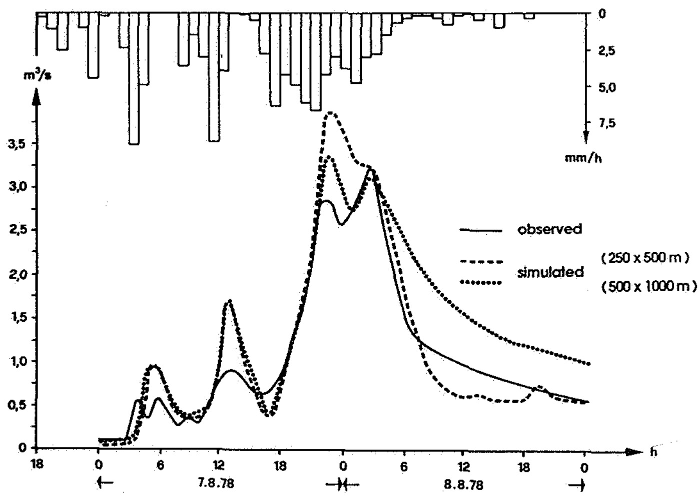


Figure 3. Observed and simulated flows with the SHE model on the Haute Menthue watershed

Physically based model are very flexible, since the user can adjust a large number of parameters. However, parameters fitting can lead into situation where a model works well, but for the wrong reasons (Klemes, 1986). For instance, for the same event of figure 3, first simulations did not reproduce correctly the first two peaks and in general the model was not able to simulate rapid responses from the Haute Menthue watershed during small rainfall events. It was considered that these quick reactions were generated by impervious areas, roads or built up sectors and rocks lying on the ground surface in the narrow valleys. Unfortunately, investigations and measurements show that this assumption was wrong, since rapid responses are the result of subsurface flow.

The last example is related to the spread of saturated areas. The TOPMODEL (Beven and Kirkby, 1979), that allows to simulate the various runoff mechanisms with a limited number of parameters, calculates the extension of saturated areas with a topography derived variable $\ln(a/\tan\beta)$, where a is the area drained by unit contour and $\beta$ is the local slope. This index takes explicitely into account the shape of the drainage basin.

Water table levels recorded in the elementary catchments during various periods enabled the verification of the adequacy of the topography index for our watershed. Figure 4 shows an example of correlation between phreatic level and the value of the topography index at the location of the piezometer. Even with a very precise Digital Terrain Model which also accounts for micro-topography, an important part of the total variance remains unexplained. Hydraulic conductivity along with many other factors influence the spatial and temporal variability of the water table. With such uncertainties, it is not reasonable to expect precise predictions. Therefore, the need to include a stochastic component in a conceptual model is confirmed.

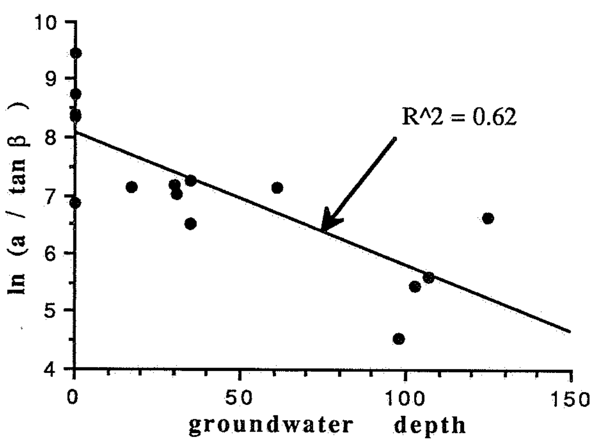


Figure 4. Relation between the topographic index ln (a/tanβ) and the minimum depth of water table for the event of 09/09/1988

## 4 Conclusions

An experimental watershed extensively monitored is a complementary tool to theoretical research conducted on hypothetical catchments. The equipment of the Haute Menthue watershed is not very sophisticated and can be followed by one person one day per week with satisfactory results. The identification of the various runoff mechanisms is the first step towards an improved conceptual modeling approach. The second concern is related to the effects of vegetation cover. The influence of forest has been shown at a small scale only. This indicates that the determination of land use effects on flood hydrographs requires a better understanding of scale problems.

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# WATER BALANCE COMPUTATIONS FOR LARGER REGIONS BASED ON CALIBRATED MODELS OF GAUGED CATCHMENTS

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## 1 Introduction

The continuously increasing stress on water resources with respect to quantity as well as quality, the conflicts arising from multifunctional use of the available water, and environmental considerations which are growing more and more important, urge for an accurate knowledge of the water resources and their distribution in time and space.
In an attempt to explore the boundary conditions for water management in Flanders, water balance computations are carried out for the Flemish Region, and for 27 geographical subregions as defined in the General Water Treatment Scheme of the Flemish Government.
In a first phase more than 50 gauged catchments are studied. The hydrological and hydrometeorological data collected during the past 40 years are incorporated in the study. A lumped system mathematical model, WABAM (WAter BAlance Model), calculating the major terms of the water balance on a monthly time base, is calibrated for these catchments. The regional variation in the water balance is analyzed, which allows for an extrapolation of the results over larger geographical units.

## 2 A lumped System Mathematical Model

The concept of the lumped system mathematical model on a monthly scale as used at the Laboratory of Hydrology was discussed in earlier papers

(A. Bladt et al. 1977, A. Van der Beken 1977, Anonymous 1985, G.L. Vandewiele 1985). However, in recent years several new models were developed and tested in a number of catchments in Belgium and in other parts of the world. Table 1 shows the model equations of one of these models.

Table 1. Model equations of WABAM

| | |
|---|---|
| $r_t = e_t \ (1-a_1^{\ (p_t + m_{t-1})/e_t})$ | (1) |
| $s_t = a_2 \ m_{t-1}$ | (2) |
| $f_t = a_3 \ m_{t-1} \ (p_t - e_t \ (1-e^{-p_t/e_t}))$ | (3) |
| $d_t = s_t + f_t$ | (4) |
| $m_t = (m_{t-1} + p_t - r_t - d_t)^+$ | (5) |

where

$p_t$ = precipitation
$e_t$ = free water evaporation
$r_t$ = actual evapotranspiration
$s_t$ = slow runoff
$f_t$ = fast runoff
$d_t$ = total runoff
$m_t$ = moisture index or storage at beginning of month t
$a_1$ to $a_3$ = model parameters
$(x)^+$ = max (0,x)

Input series for the model are free water evaporation ($e_t$), calculated by an adapted Penman formula (F. Bultot et al. 1983) and areal precipitation ($p_t$). The model calculates the actual evapotranspiration ($r_t$), fast ($f_t$), slow ($s_t$) and total runoff ($d_t$), net-infiltration and changes in water storage. The actual evapotranspiration is calculated as a fraction of the free water evaporation (eq. 1). This fraction depends on the ration between the available water in the catchment ($p_t + m_t$) and the free water evaporation ($e_t$). Slow runoff is related to the moisture condition of the catchment (eq. 2) while the fast runoff (eq. 3) depends on the precipitation and the moisture condition in the catchment. Eq. 5 gives the water balance equation.

$a_1$, $a_2$ and $a_3$ are model parameters, all smaller than 1. They are estimated by automatic optimization, based on the Gradient Method, for gauged catchments. A monthly discharge record of at least 8 years is necessary to obtain reliable results. Figure 1 gives an example of some input and output series of the model.

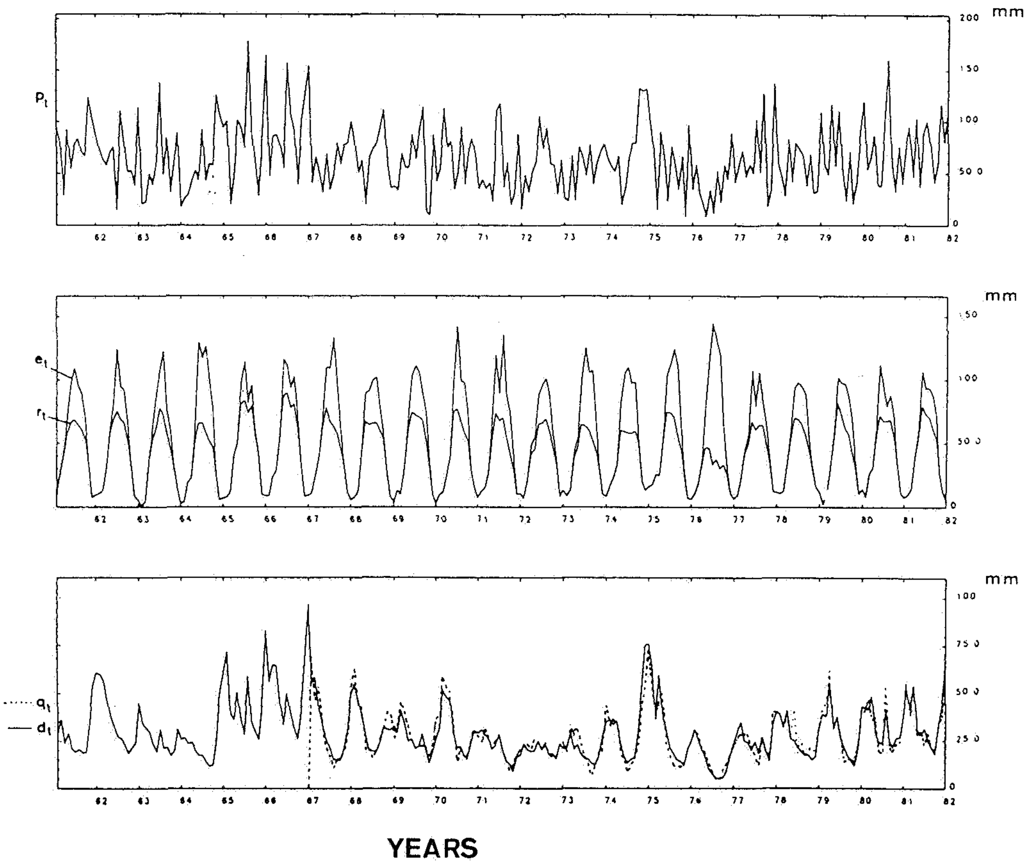


Figure 1. Input and output series of WABAM for the Grote Nete and Itegem ($p_t$: precipitation, $e_t$: evaporation, $r_t$: actual evapotranspiration, $d_t$: calculated discharge, $q_t$: measured discharge)

## 3 Regional variation

The model was calibrated and the water balance terms calculated for more than 50 gauged catchments in the Flemish region. It allowed for a study of the regional variation of the water balance terms. As an example Figure 2 shows the regional distribution of the fast runoff in % of the total precipitation. The importance of the fast runoff in the water balance diminishes clearly from NW to SE. In the NW more than 24% of the precipitation is discharged within the same month. In the SE of Flanders on the contrary, it represents less than 10%. This picture clearly reflects the geological conditions in the catchments. In the western catchments the subsurface is characterized by the presence of Tertiary clay layers. The importance of these clay layers is reducing significantly to the east where the subsurface consists mainly of highly permeable sediments such as sands and limestone. On the other hand, soils are becoming less sandy and more silty to the south. The capacity for water storage in soil and subsurface is significantly higher in the south-eastern catchments. This is reflected in a higher evapotranspiration, lower direct runoff and higher net-infiltration.

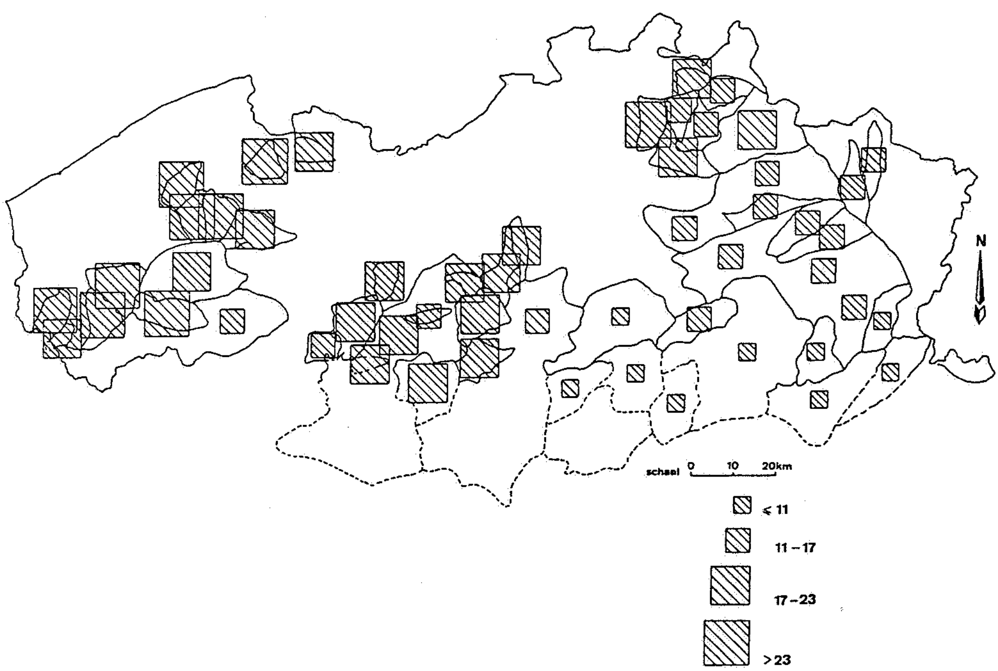


Figure 2. The fast runoff component in % of the precipitation for gauged catchments in Flanders (1951-1985)

The values of the model parameters are related to the physiographic characteristics of the basins, such as geology, topography, land use etc. In some cases these relationships are very significant as shown in Figure 3. The example gives the relationship between the evapotranspiration parameter ($a_1$) and the lithological characteristics of the subsurface in the catchment. The percentage of the catchment occupied by a permeable subsurface (e.g. sands and limestone) was taken representative for the latter.

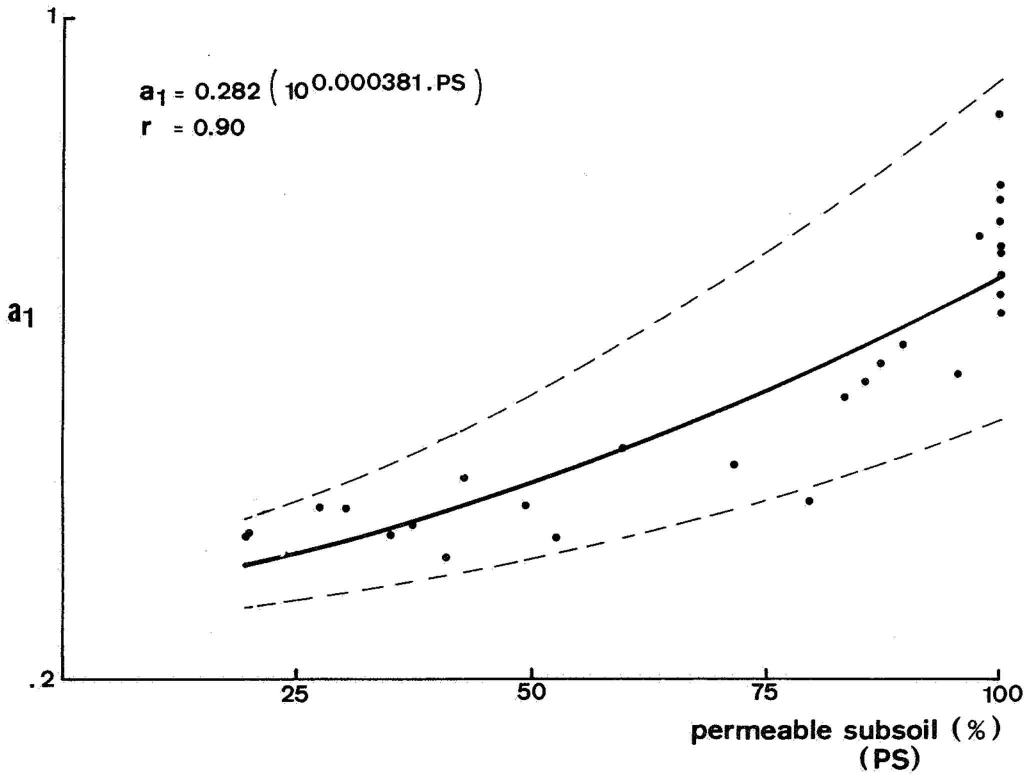


Figure 3. Relation between the evapotranspiration parameter $a_1$ and the percentage permeable subsurface (PS) in the catchments

# 4 Water balance computations for larger regions

To calculate the water balance for larger geographical regions by means of WABAM, to requirements must be fulfilled : (1) input series of free water evaporation and areal precipitation must be available and (2) the value of the three model parameters must be known for that particular region.

For the free water evaporation the data of Ukkel were recognized as being representative for the whole Flemish Region. The data are available since 1900. Data of areal precipitation are available for all subregions since 1951. This means that a simulation between 1951 and 1987 is possible. The simulation period can be extended considerably if the point precipitation at Ukkel is used, after applying monthly correction factors for the region under consideration. The precipitation at Ukkel is available from 1833 onwards (G.L. Dupriez and R. Sneyers, 1978), which allows for a simulation between 1900 and 1987.

Parameter values for the larger subregions are not ready available. The calibration of WABAM is not possible as measured discharge data do not exist. The values of $a_1$, $a_2$ and $a_3$ for each subregion can be estimated by extrapolating the results obtained under Section 3.

Some subregions incorporate a gauged catchment which can be considered as representative for the subregions. For other subregions the parameter values were established by applying the regression equations with the basin characteristics e.g. lithology of the subsurface.

The water balance of the subregions was simulated for the period 1900-1985 and Figure 4 shows a result of this simulation. For the blank areas no parameter values could be obtained, based on the approach discussed above. As such, WABAM is not applicable here. It concerns polder areas and tidal river reaches of the Scheldt basin where good data of gauged catchments are lacking. On the other hand, the basin characteristics are significantly different from those of the gauged catchments, so that an application of the regional approach is not possible.

The water balance of the Flemish Region (not taking into account the blank areas) for the period under consideration is as follows: 66.2% of the precipitation is evaporated, 18% is discharged as fast runoff, 15.8% as slow runoff.

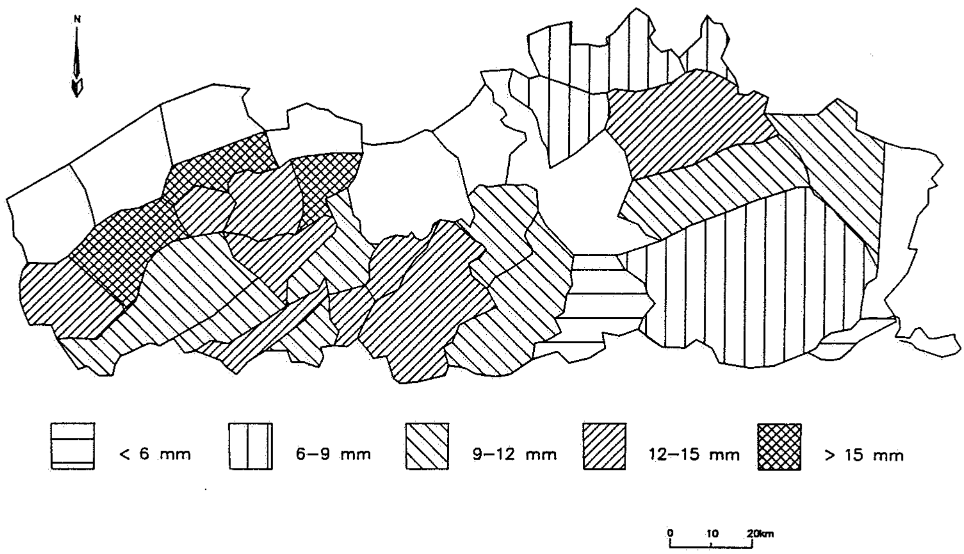


Figure 4. Monthly mean fast runoff for geographical subregions (1901-1985)

## 5 Conclusions

More than 50 gauged catchments of the Flemish region have been used to calibrate a mathematical model, WABAM, with three parameters for actual evapotranspiration, slow and fast runoff. The study of the regional variability of the water balance terms and the parameters with respect to physiographic characteristics of the catchments has revealed interesting relationships. They allow for an extrapolation of the results to ungauged catchments and larger geographical units. Once the parameter values are well determined, the simulation of all terms of the water balance equation is possible for periods where rainfall and evaporation data are available. In this way the overall water balance of the Flemish region, not taking into account the polder areas and the tidal reaches of the Scheldt basin, was calculated.

Notes

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# WATER BUDGET OF A BROADLEAVED SCLEROPHYLLOUS FORESTED CATCHMENT

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Abstract

The small watershed approach was used to determine the main water fluxes in a 4.3 ha watershed underlain by metamorphic schists and covered by a dense holm-oak (*Quercus ilex* L.) forest in the Montseny mountains (NE Spain). Mean annual precipitation for the 6-year study period (from August 1983 to July 1989) was 857 mm while mean annual streamflow was 442 mm. Mean evapotranspiration, calculated as the difference between mean annual precipitation and mean annual streamflow, was 415 mm or 48% of precipitation. Interannual variability was maximum for streamflow which varied from 179 mm in the driest year to 725 mm in one of the wettest. Annual streamflow was positively correlated ($r=0.97$ $p<0.001$) with annual precipitation while no correlation was found between annual evapotranspiration and precipitation, a similar response to forested ecosystems under more cold-humid climates and contrasted to ecosystems under a more xeric climate as in the case of other mediterranean watersheds receiving less precipitation.

## 1 Introduction

Undisturbed forested ecosystems strongly regulate the amount and pathways of water flowing through the watershed. The use of watertight watersheds as units of study has provided important information on the distribution of input water between streamflow and evapotranspiration, a process which is highly controlled by climate and vegetation. Under cold-temperature humid climates, streamflow is usually equal or higher than evapotranspiration (e.g. Likens et al., 1977), but little is known of the more xeric, highly episodic Mediterranean climate except for the work of Piñol et al. (1988) and Piñol (1990) at the Prades mountains (Tarragona, Spain). Our purpose is to present here the water budget for 6 years in a Mediterranean forested watershed in the Montseny mountains (Barcelona, Spain) and discuss its water yield in relation to the precipitation variability, both on an annual and a monthly basis.

## 2 Study area and methods

The experimental watershed, named TM9, is located at La Castanya Biological Station (41° 46'N, 2°21'E) in the Montseny mountains, 40 km to the NNE of Barcelona. It is a north-facing, 4.3 ha watershed, ranging in elevation from 700 to 1035 m a.s.l, and with a mean slope of 36°. The bedrock is a metamorphic schist formed mainly by quartz, sericite, albite and chlorite. The soils are very stony, sandy-loam acidic xerochrepts, 0.4-1.5 m deep. Climate is montane Mediterranean with an estimated mean annual temperature of 9-10°C. Mean annual precipitation is 857 mm but there is a large interannual variability in both the annual amount and the monthly distribution of precipitation. The watershed is completely covered by a dense holm oak (*Quercus ilex* L.) forest that was coppiced for charcoal production until 25-30 years ago, and has not been disturbed since then.
Streamflow is continuously recorded at a gaging station at the watershed outlet. The weir is a thin-crest, 60° V-notch. Precipitation amount is measured weekly with a standard rain gage beside the weir.

# 3 Results

## 3.1 Precipitation

Water fluxes reported here refer to the 6-year period from August 1st 1983 to July 30th 1989. The average annual precipitation for these 6 years is 857.2 mm (Table 1). This 6-year average is thought to be close to the mean annual rainfall at La Castanya, since the mean precipitation measured during 24 years in the village of Montseny, located at 522 m a.s.l. and 5 km away from TM9, was 860 mm/year.

Table 1 Annual precipitation (P), streamflow (Q) and actual evapotranspiration ($E_a$) at TM9. The 6-year mean and deviation statistics are also included. All data are expressed in mm

| Year | P | Q | $E_a$ |
|---|---|---|---|
| 1983-1984 | 1052.8 | 702.8 | 350.0 |
| 1984-1985 | 873.1 | 403.6 | 469.5 |
| 1985-1986 | 718.5 | 328.2 | 390.3 |
| 1986-1987 | 808.4 | 315.6 | 492.8 |
| 1987-1988 | 1049.4 | 725.6 | 323.8 |
| 1988-1989 | 640.8 | 179.1 | 461.7 |
| Mean | 857.2 | 442.5 | 414.7 |
| s.d. | 169.6 | 222.7 | 69.8 |
| s.e. | 69.3 | 90.9 | 28.5 |
| c.v.(%) | 19.8 | 50.3 | 16.8 |
| Range | 412.0 | 546.6 | 169.0 |

During the study period, precipitation in the driest year (1988-1989) was 640.8 mm, whereas in the wettest year (1983-1984), it was 1052.8 mm. The difference between them spans in 412 mm, 64% of the lowest value. The coefficient of variation of the annual precitation during the 6-years is 19.8% (Table 1), nearly doubling the variation of areas in the northern hemisphere under a more equable climate (e.g. at Hubbard Brook this value is 12.2% for a 19-year period. (Likens et al., 1977)).

For a given month, precipitation at TM9 is highly variable from year to year. For the study period, maximum deviations form the mean precipitation occur in summer and winter months: e.g. July, January and September have coefficients of variation of 104%, 104% and 97%, respectively. Minimum deviations from mean precipitation are in spring and autumn: e.g. April, November and June have coefficients of variation of 46%, 54% and 60%, respectively (Table 2). Despite this very high variability, a general pattern in precipitation emerges from the 6-year averaged values (Figure 1), where maximum precipitation tends to concentrate in autumn (October and November) and spring (May). This pattern conforms to the general precipitation distribution in Mediterranean climates of eastern Spain (Walter, 1976).

Snowfall during the study period ranged from 0% of annual precipitation in 1987-88 and 1988-89 to 17% in 1985-86. Generally, after a snowfall, snow persists on the soil for no more than a week.

## 3.2 Streamflow

The annual streamflow is even more variable than precipitation. The 6-year average value is 442.5 mm, but streamflow ranges from 179.2 mm in the driest year (1988-89) to 725.6 mm in one of the wettest (1987-88, Table 1), a 4-fold difference.

On a monthly basis, highest variability ocurred in October and January, with coefficients of variation of 156% and 158% respectively, whereas minimum variation ocurred in the summer months of July, August and September which also delivered the minimum streamflow (Table 3). The 6-year average pattern of monthly discharge is shown in Figure 2. Here, despite the high variability mentioned, two peaks are clearly apparent, one for late autumn-early winter, and another in mid-spring. Normally, half of the annual streamflow is produced during only one or two months of very high discharge, giving a pronounced seasonality in runoff.

Table 2 Monthly precipitation (mm) at TM9

| Month | 1983-84 | 1984-85 | 1985-86 | 1986-87 | 1987-88 | 1988-89 | mean | c.v.(%) |
|---|---|---|---|---|---|---|---|---|
| August | 100.2 | 102.8 | 41.5 | 35.0 | 11.5 | 32.9 | 54.0 | 70.7 |
| September | 9.0 | 96.5 | 9.4 | 29.9 | 15.4 | 46.8 | 34.5 | 97.4 |
| October | 66.1 | 11.2 | 90.8 | 157.1 | 261.9 | 66.1 | 108.9 | 81.4 |
| November | 207.4 | 231.0 | 94.9 | 39.6 | 90.4 | 193.8 | 142.9 | 54.4 |
| December | 105.9 | 61.1 | 18.0 | 35.4 | 126.6 | 3.6 | 58.4 | 84.2 |
| January | 3.1 | 29.4 | 122.7 | 87.6 | 221.2 | 16.1 | 80.0 | 103.6 |
| February | 50.7 | 6.9 | 68.7 | 90.7 | 0.8 | 38.5 | 42.7 | 81.7 |
| March | 149.1 | 51.6 | 66.7 | 43.4 | 12.1 | 28.9 | 58.6 | 82.1 |
| April | 21.9 | 48.0 | 102.4 | 66.2 | 105.4 | 94.8 | 73.1 | 46.1 |
| May | 273.0 | 186.1 | 39.7 | 111.2 | 131.2 | 37.6 | 129.8 | 69.5 |
| June | 63.1 | 28.0 | 17.8 | 10.8 | 64.1 | 59.3 | 40.5 | 60.2 |
| July | 3.3 | 20.5 | 45.9 | 101.5 | 8.8 | 22.4 | 33.7 | 107.7 |
| Annual | 1052.8 | 873.1 | 718.5 | 808.4 | 1049.4 | 640.8 | 857.2 | 19.8 |

Table 3 Monthly streamflow (mm) at TM9

| Month | 1983-84 | 1984-85 | 1985-86 | 1986-87 | 1987-88 | 1988-89 | mean | c.v.(%) |
|---|---|---|---|---|---|---|---|---|
| August | 7.9 | 10.0 | 7.7 | 5.7 | 6.4 | 6.3 | 7.3 | 21.3 |
| September | 6.4 | 13.3 | 6.0 | 5.5 | 5.9 | 6.3 | 7.2 | 41.4 |
| October | 7.6 | 9.6 | 8.0 | 21.2 | 127.4 | 9.4 | 30.5 | 156.4 |
| November | 89.8 | 121.5 | 22.5 | 14.9 | 65.1 | 83.8 | 66.3 | 62.1 |
| December | 131.5 | 56.0 | 10.3 | 16.5 | 148.6 | 18.4 | 63.6 | 96.9 |
| January | 21.9 | 16.2 | 11.0 | 33.3 | 217.4 | 10.6 | 51.7 | 157.8 |
| February | 11.7 | 10.3 | 58.0 | 52.4 | 31.5 | 8.1 | 28.7 | 77.7 |
| March | 60.8 | 10.4 | 100.9 | 39.6 | 12.4 | 7.8 | 38.7 | 95.3 |
| April | 65.7 | 8.5 | 60.4 | 52.9 | 10.8 | 8.7 | 34.5 | 80.9 |
| May | 229.9 | 117.0 | 26.0 | 43.8 | 66.5 | 8.6 | 82.0 | 99.5 |
| June | 56.7 | 21.9 | 10.5 | 18.6 | 24.1 | 6.9 | 23.1 | 76.6 |
| July | 12.9 | 8.9 | 7.0 | 11.3 | 9.5 | 4.2 | 9.0 | 34.6 |
| Annual | 702.8 | 403.6 | 328.3 | 315.7 | 725.6 | 179.1 | 442.5 | 50.3 |

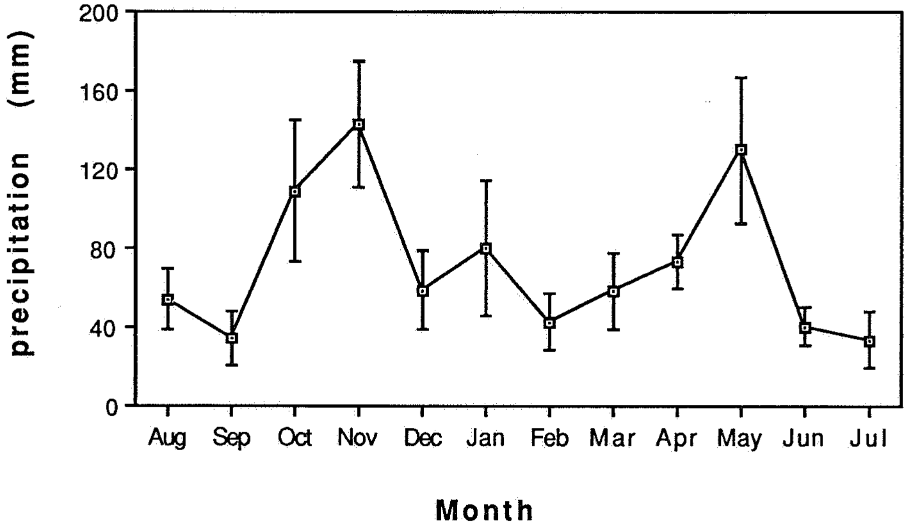


Figure 1 Average monthly precipitation at TM9 for the 6-year period from August 1983 to July 1989. The vertical bars are one standard error of the mean

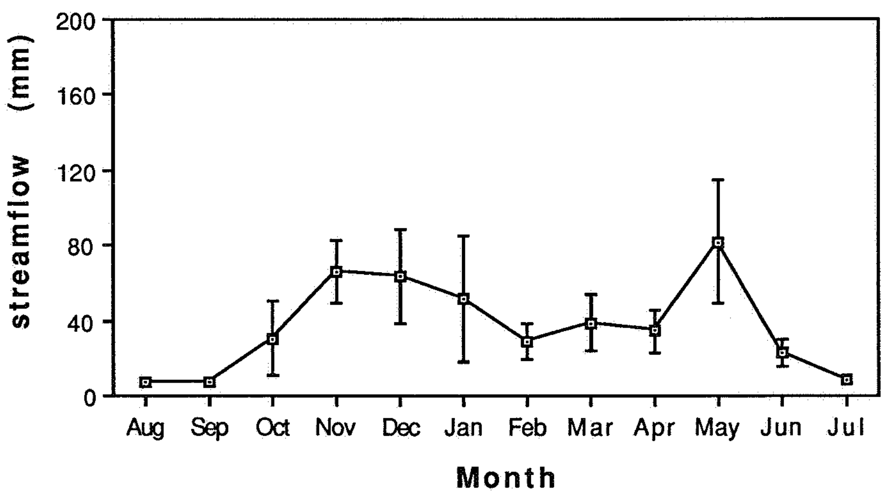


Figure 2 Average monthly streamflow at TM9 for the 6-year study period from August 1983 to July 1989. The vertical bars are one standard error of the mean

## 3.3. Evapotranspiration

Evapotranspiration is here calculated as the difference between annual precipitation and streamflow. This method is widely used in catchment hydrology studies and assumes that deep water losses are negligible and that there are no major differences in the amounts of water stored in the watershed at the start and at the end of any given water year. The average annual evapotranspiration for the 6-year period is 414.7 mm (Table 1). Interannual differences are of less magnitude than in precipitation and streamflow, its coefficient of variation being 16.8% (Table 1). Wet years produce the highest drainage: in 1983-84 and 1987-88, drainage amounts to 67% and 69% of respective annual precipitation, while drier years produce much less drainage: in 1988-89 streamflow is only 28% of precipitation. This stems from a direct dependence of annual streamflow on annual precipitation at TM9. Linear regression of annual streamflow on annual precipitation presents a high correlation ($r=0.97$, $p<0.001$, Figure 3). Annual evapotranspiration however, is little affected by variation of precipitation amount (Figure 3), its linear regression on precipitation being non significant ($r=0.67$, $p>0.05$).

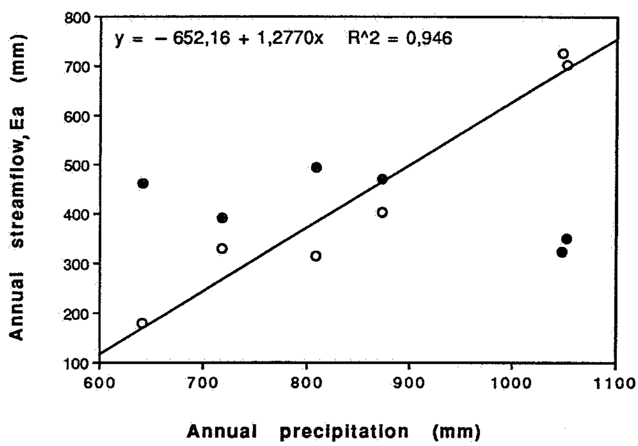


Figure 3 Annual streamflow (open circles) and evapotranspiration ($E_a$, filled circles) represented against annual precipitation. Only annual streamflow is significantly correlated with precipitation and its regression is given at the top of the figure. The regression line is also represented.

# 4 Discussion

At TM9, on average, 51.6% of the annual precipitation is exported through streamflow and the remaining 48.4% is evapotranspired, that is, precipitation is equally distributed between streamflow and evapotranspiration. This, and the fact that streamflow is highly correlated with precipitation, suggest that the holm oak forest at TM9 is not strongly limited by lack of water and that the hydrological behaviour of the watershed resembles that of more humid ones. For example, from the review by Bosch and Hewlett (1982), the average drainage of 57 humid-temperate forested watersheds (those receiving more than 900 mm) was 52%. At Coweeta, a hydrologic station under a humid, warm-temperate climate in North Carolina (U.S.A), annual streamflow is positively correlated with annual precipitation (Swift et al., 1987). At Hubbard Brook (N.H., U.S.A), under humid, cold-temperate conditions, annual streamflow is positively correlated to annual precitation while annual evapotranspiration is relatively constant and independent of the amount of precipitation (Likens et al., 1977).

On the other hand, watersheds under more xeric conditions behave quite differently, with evapotranspiration as the dominant water flux. From data reviewed by Bosch and Hewlett (1982), 9 xeric watersheds (here defined as receiving less than 600 mm/year of precipitation) drained on average, only 12.5% of precipitation. This is also the case of another Mediterranean catchment (L'Avic, Prades) 140 km to the southwest of TM9 which is similar in vegetation cover and lithology to TM9 but receives only 548 mm of annual rainfall, 36% less than TM9. At L'Avic, the water partition is clearly dominated by evapotranspiration, which amounts to 92% of annual precipitation (average for 7 years, Piñol 1990), streamflow accounting only for the remaining 8%. Moreover, at L'Avic, the linear regression of annual streamflow on annual precipitation is not significant, while annual evapotranspiration is highly correlated with annual precipitation ($r=0.98$, $p<0.001$, Piñol 1990). These differences in hydrological behaviour are better understood if another hydrologic variable, the potential evapotranspiration, is considered, as was suggested by Piñol et al. (1988).

Potential evapotranspiration is the evaporative demand of the watershed provided that there is no limitation in water availability. If precipitation is in excess of potential evapotranspiration, the evaporative demand of the watershed can be totally satisfied and excess water input is drained to the stream. In these cases, the more it rains the more water is drained, giving rise to a positive relationship between annual precipitation and streamflow. Our watershed conforms to this model because on average it receives precipitation in excess of its potential evapotranspiration (calculated by Savé (1986) to be of 685 mm during 1980 using the Thorntwaite formula), and behaves similarly to watersheds in northern latitudes. Under more xeric conditions, potential evapotranspiration is greater than precipitation and then, only a small fraction of the precipitation is drained (mainly during a few major storm events) while a major part is used up in evapotranspiration. Years with more precipitation can account for a greater part of the evaporative demand, and therefore a direct relationship between precipitation and evapotranspiration results. This is the case of L'Avic, which receives on average 548 mm and has a potential evapotranspiration (measured by a Piché evaporimeter) of 1050 mm/year (Piñol 1990).

From the above considerations, it is clear that on an annual basis, the holm oak forest at TM9 does not suffer from a lack of water. However, in a monthly basis, it may exist a shortage in available soil moisture during the warm season. In fact, when the 6-year averaged monthly streamflow is regressed against precipitation, months in the warm season (from July to October) have pronounced negative residuals, draining much less water than that predicted with the whole set of monthly values (Figure 4). June, a warm month, does not show a marked negative residual because it is a month largely influenced by usually heavy rains in May which produce high stormflows queuing into June. Because of large precipitations in May producing humid soil conditions until June, we can assume that the beginning of the growing season for the watershed vegetation takes place under good moisture conditions. However, at the peak of the warm season (from July to September) nearly all precipitation is retained by the watershed, producing the highest monthly drainage deficits (defined as monthly precipitation minus monthly streamflow) of the year. These drainage deficits are probably related to evapotranspiration because, although we do not know exactly the effect of changes in stored soil water at the end of each month, there is a positive relationship between monthly water deficit and precipitation while streamflow is not significantly correlated to precipitation, an analogous response to that of annual evapotranspiration and annual precipitation in xeric sites. As an example of the high water retention capacity in the warm season, 6 storm events during the July-September period of 1984-1985 delivering together 207 mm, drained on average only 1.3% of precipitation and produced only 1% of the total annual runoff.

During the winter and autumn months (from November to May) the evaporative demand is lower and monthly precipitation is not correlated with monthly drainage deficit. Surprisingly, it is neither correlated to monthly streamflow as it could be expected. This is because some winter months have moderate precipitation inputs but due to very humid antecedent conditions produced by rains in previous months, they have very large water outputs. As a general pattern, during winter and autumn months, precipitation is either, a) equally distributed between monthly drainage and evapotranspiration, or b) mainly or totally exported through drainage. In some stormflow events under very humid antecedent conditions, stormflow can account up to 90% of the event precipitation (Avila, 1987).

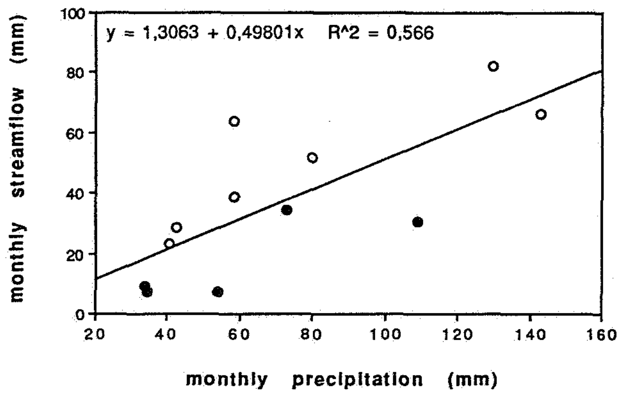


Figure 4 Relationship between mean monthly streamflow and mean monthly precipitation for the period August 1983 to July 1989. The regression equation and the regression line are represented. Filled circles are warm months (June to October, both included)

TM9 is also similar to northern watersheds when the Hewlett and Hibbert (1967) response coefficient (quickflow/total runoff) is considered. For the hydrologic year 1984-85, with a water export of 404 mm, 30% was quickflow and the remaining 70% was delayed flow. This response coefficient is quite high and similar, e.g. to the watershed 6 of Hubbard Brook (Hewlett and Hibbert, 1967). Thin soils and steep slopes would account for the quick response at TM9. Although quick responses are usually attributed to hortonian overland flow, at our site an important proportion of quickflow seems to be generated by subsurface flow. From the solute behaviour during storm events at TM9, Avila (1987) concluded that subsurface flow (as quickflow or delayed flow) accounts, on an annual basis, for 99% of total runoff. Overland flow would account for the remaining 1% of total runoff and is produced in summer storm events under very dry antecedent conditions. This very small proportion can be attributed to the high infiltration rates of these forested soils. In fact, summer storm events only export around 1% of precipitation, probably the water precipitated on the stream channel. Because of the dominance of subsurface flow in the annual drainage, there is little erosive effect on the watershed slopes. Moreover, streamwater chemistry will be strongly influenced by biogeochemical interactions within the soil.

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# A COMPARISON OF SIX UNSATURATED ZONE MODELS WITH DATA FROM THE 'HUPSELSE BEEK' CATCHMENT, THE NETHERLANDS

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## 1 Introduction

Mathematical modelling of the landphase of the hydrological cycle is a widely used and recognized approach in water resources planning and management. In general transport of water occurs by flow through the unsaturated and saturated zones and by flow through open channels.
Only a few models exist, which describe the landphase-process as a coupled system. Normally an isolated part of the system is modelled, taking the other parts of the system as prescribed, simplified boundaries or neglecting them.
Here, only models for simulating water transport and water balances in the unsaturated zone are considered.
Knowledge of flow processes in the unsaturated zone is of eminent importance for proper agricultural watermanagement, for water quality studies and, more recently, in atmospheric modelling.
Because of the fact that models have been developed for different purposes, it may be expected that they vary in complexity.
For practical purposes an one-dimensional representation of the flow process in the unsaturated domain is generally seen as acceptable.
However, it implies that no account is made for spatial variation of flow characteristics in the horizontal direction. In practice this must lead to a careful interpretation to what extend the areal representativeness of the absolute model-results is valid.
In this study the calculated results from the different models are compared as much as possible with point measurements and thus no

interpretation of the results with respect to areal representation ought to be considered.

## 2 Models

In this study six models have been used to compute transient unsaturated flow in a vertical soil column and evapotranspiration from its cropped surface. The physical system is shown schematically in Figure 1, the soil column extends from just below the freatic surface to the soil surface.

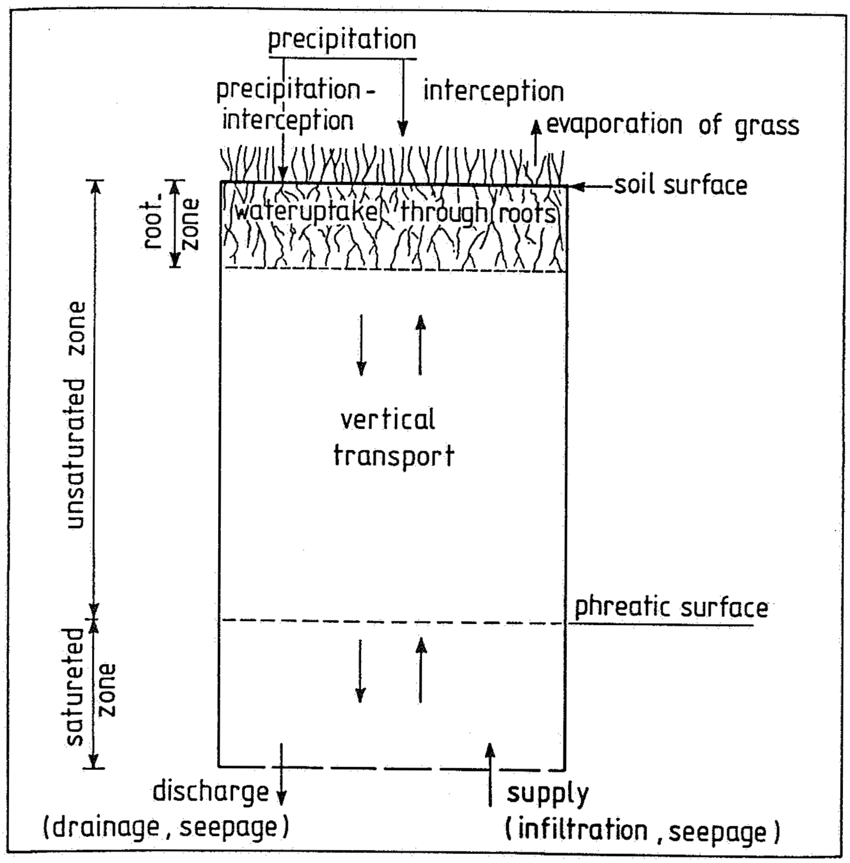



Figure 1. Schematization of water transport in the upper soil layers.

The non-linear second order differential equation describing unsaturated flow in one direction is the Richards equation including a sink term

$$C_w(h_p)\,\frac{\partial h_p}{\partial t} = \frac{\partial}{\partial z}\left[k(h_p)\left(\frac{\partial h_p}{\partial z} + 1\right)\right] + S \qquad (1)$$

in which $C_w$ = differential moisture capacity ($m^{-1}$)
$h_p$ = pressure head or matrix potential (m)
S = sink or source term ($m^3 m^{-3} d^{-1}$)
t = time (d)
z = vertical space coordinate (m)

Numerical solution of the equation is in principle a straight forward procedure, although the non-linearity which is caused by the functions $C_w(h_p)$ and $k(h_p)$ may give rise to practical problems.
The models, of which five are frequently applied in the Netherlands and have been used in an earlier study of comparison, are:

- DAIR (Daily Irrigation), Petrovic (1989)
- DEMGEN (Demand Generator), van Vuuren (1984)
- MUST (Model for Unsaturated flow above a Shallow water Table), de Laat (1980)
- ONZAT, van Drecht (1983)
- SOMOF (Soil moisture flow), Gilding (1983)
- SWATRE (Soil Water, Actual Evapotranspiration Rate, extended), Belmans e.o. (1983)

## 2.1 Finite difference models

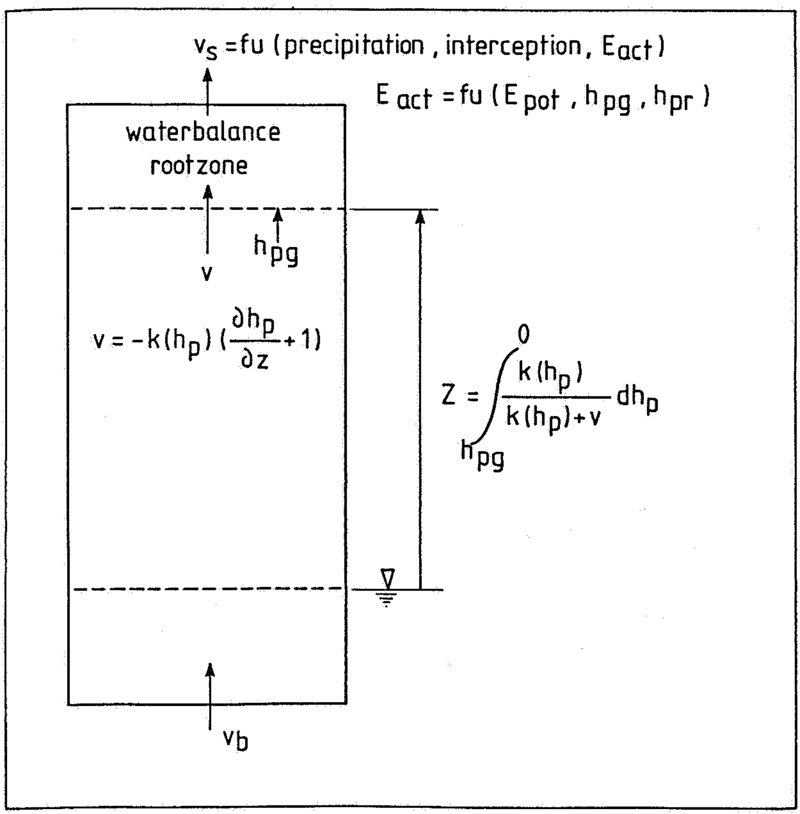
SWATRE, SOMOF and ONZAT are finite difference models, solving equation (1) by generating a system of difference equations. Although each of the models write somewhat different equations they all have to be linearized in order to reach a solution. SWATRE and ONZAT use explicit and iterative methods, while SOMOF applies a predictor-corrector scheme. For a detailed description the reader is referred to the literature references on each of the models.
The finite difference models are simulating the dynamic water movement in discrete steps. At times when gradients of the hydraulic head are

very high this may lead to very small time steps (order of seconds) so as to avoid stability problems. Such situations did not occur in this study.

## 2.2 Pseudo steady-state models

DAIR, DEMGEN and MUST are models operating on a different principle: they consider a steady flow during each timestep (usually one day), based on the notion that relatively large potential changes are needed to substantially alter the capillary rise.

These models divide the soil column above the freatic surface into two parts: the root zone and the subsoil, see Figure 2. The gradient of the hydraulic head in the root zone is neglected, assuming that movement of water is governed by the uptake of roots only.




gure 2. Representation of pseudo steady-state models.

De Laat (1980) has shown that a steady state situation is governed by two parameters for which these models use the steady flux in the subsoil and the saturation deficit in the root zone ($S_r$). Capillary rise can be expressed by means of so called pressure profiles, which give the relation between the pressure head and the height above the water table for a given value of the vertical flux ($v_z$). Such profiles may be computed according to:

$$z = \int_{h_p}^{o} \frac{k(h_p)}{v_z + k(h_p)} dh_p \qquad (2)$$

Combination of pressure profiles and the soil moisture characteristic leads to moisture content profiles, from which the saturation deficit $S_u$ (in the subsoil) may be obtained, the saturation deficit in the root zone is a function of the pressure head only. It follows that there exists a relation between the total saturation deficit $S_u$, $S_r$ and $v_z$. Before the solution starts the model computes a large number of possible combinations between saturation deficits, groundwater depths and vertical fluxes. The actual computation consists of finding the flux situation, by means of an interative procedure, which satisfies the boundary conditions.

## 2.3 Evapotranspiration

The vegetation around the Hupsel observation station is grass. It was therefore assumed that evaporation of bare soil could be neglected and hence all evapotranspiration is due to plant transpiration. All models compute the actual evaporation $E_{act}$ from the potential evapotranspiration $E_{pot}$. However the relation they use between the ratio $E_{act}/E_{pot}$ and $h_p$ is specific for each of the models; also it is recognized that the value of $h_p$ at which reduction starts is dependent on the evaporative demand from the atmosphere, that is on the $E_{pot}$ itself. Details on these matters can be found in the literature references.

The finite difference models apply the evaporation as the sink term S in equation (1), while in the pseudo-steady state models it is a boundary flux at the top of the column.

# 3 Data

All data of calibration and verification have been collected at the meteorological station in the experimental catchment 'Hupselse Beek'.
The main features of the catchment are: an area of 6,5 $km^2$, a slightly undulating topography (≈ 1%), a shallow profile of sandy soil with spots of boulder clay in the underground and which overlays a very thick (up to 40 m) layer of impermeable miocene clay. The catchment is well drained and is covered mainly by grassland. For an extended description we refer to Warmerdam e.o. (1982). For calibration and verification daily input and output data have been used over the periods 1976-1978 and 1979-1982 respectively. More information on the data will be summarized hereafter.

## 3.1 Precipitation

Precipitation has been collected by a raingauge at groundlevel. During periods of snow data of a second raingauge, provided with a 40-cm high ring and a heating element, have been used.

## 3.2 Groundwater depth

Daily values have been used, averaged from 20-min observations. In 'Hupsel' groundwaterlevels may fluctuate occasionally by 20 cm or more over one day.

## 3.3 Potential evapotranspiration (ET-pot)

The method applied is the one according to Thom & Oliver (1977). The surface roughness length $z_{om}$ has an estimated value of 0.01 m and the basic crop resistance $r_c$ a value of 65 sec/m for grass.
The aerodynamic resistance $r_a$ (sec/m) has been calculated from the daily mean windspeed and consequently n, defined by $r_c/r_a$ is also a variable quantity.

DAIR applies a different $E_{pot}$-formulation, for which the results were tuned with the Thom & Oliver data.

## 3.4 Actual evapotranspiration (ET-act)

For the growing season (1st of April - 1st of October actual evapotranspiration has been indirectly estimated by the aerodynamic profile-energy budget method (Stricker and Brutsaert, 1978). The results of this method have been compared with the Bowen ratio method for several growing seasons. As an example Figure 3 shows the results for the summer period of 1981 and Table 1 summarizes some statistical characteristics of the results of both methods.

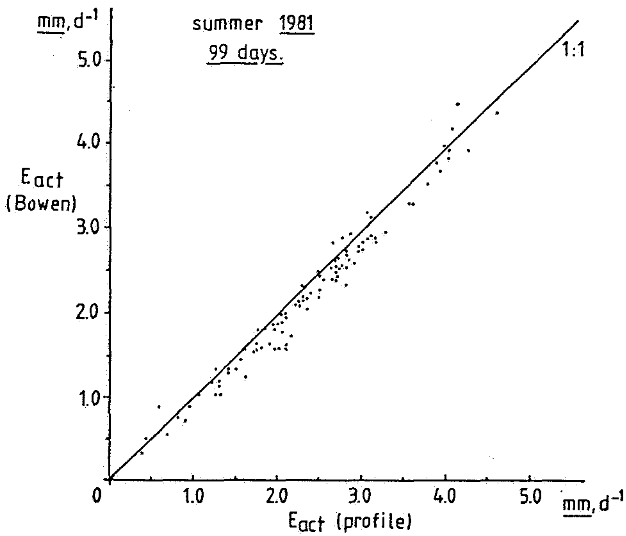



Figure 3. Comparison of daily values of E-act for profile method versus Bowen ratio method. An example for one year.

## 3.5 Soil moisture data

Bimonthly data by neutron measurements were available. Measuring depths were 10, 20, 30, 40, 60, 80, ...., 200 cm. Soil moisture changes could be calculated by on site calibrated conversion curves.

Table 1. Statistical comparison of the results of the aerodynamic profile-energy budget method and the Bowen ratio method.

| | $E_{ACT}$ (profile) Average mm/etm | $E_{ACT}$ Bowen Average mm/etm | Number of days | Variation coefficient[1] (%) | Correlation coefficient | Linear regression coefficients a | b |
|---|---|---|---|---|---|---|---|
| 1979 | 2,25 | 2,31 | 76 | 8,5 | 0,974 | 0,96 | 0.15 |
| 1980 | 2,09 | 2,04 | 88 | 9,8 | 0,972 | 0,982 | -0.01 |
| 1981 | 2,38 | 2,25 | 99 | 8,5 | 0,985 | 0,992 | -0.11 |
| 1982 | 2,50 | 2,36 | 49 | 9,6 | 0,977 | 0,987 | -0.11 |

1) Definition: $S = \frac{\sqrt{(x-y)^2}}{\bar{x}}$ with $x = E_{ACT}$ (profile) and $y = E_{ACT}$ (Bowen)

2) $E_{ACT}$ (Bowen) $= a \cdot E_{ACT}$ (profile) $+ b$

## 3.6 Other data

In addition to the above listed time dependent data, some time independent parameters of the models must be known. Root zone depth was estimated at 25 cm but most models used 30 cm. Furthermore soil physical information was available from the meteorological site, for which both pF- and $k(h_p)$-curves were determined for each horizon (Stiboka, 1983).

# 4 Calibration

The models were supplied with data of three years, 1976-1978. The year 1976 had an extremely dry growing season, while 1977 and 1978 were moderately humid years, without apparent soil moisture deficits.
Calibration of the models was done by comparing the computed 10-days sums of actual evaporation with the given data. Most models adjusted parameters in the relation between the ratio $E_{act}/E_{pot}$ and $h_p$, including the value of the pressure head at which reduction started. It is noticed here that for all models except DAIR, measured groundwater depths have

been chosen as lower boundary condition. DAIR calibrated a Q-h relationship for computing the groundwater level in the verification period as an other output variable.

## 5 Verification

The models were tested mainly on their capability to simulate the real course of evaporation.
The totals of the actual evaporation during the growing seasons of the verification period are shown in Table 2, all models perform well as the largest differences amount to 11%.

Table 2. Potential and actual ET-sums for all growing seasons [mm].

| Period | $E_{pot}$ | $E_{act}$ | DEMGEN | MUST | DAIR | ONZAT | SOMOF | SWATRE |
|---|---|---|---|---|---|---|---|---|
| Growing season 76 | 502 | 365 | 379 | 346 | 345 | 361 | 382 | 361 |
| Growing season 77 | 361 | 359 | 362 | 359 | 366 | 355 | 360 | 361 |
| Growing season 78 | 371 | 381 | 372 | 368 | 367 | 359 | 370 | 371 |
| Growing season 79 | 382 | 393 | 382 | 380 | 381 | 341 | 382 | 382 |
| Growing season 80 | 411 | 394 | 413 | 387 | 384 | 380 | 383 | 394 |
| Growing season 81 | 396 | 406 | 395 | 389 | 386 | 391 | 395 | 396 |
| Growing season 82 | 440 | 416 | 413 | 393 | 368 | 387 | 399 | 395 |

An important aspect is wether the evaporation reduction $E_{pot}$-$E_{act}$ which is responsible for the retardation of crop growth, is predicted correctly. Extended periods of evaporation reduction occurred only during the growing season of 1982. The cumulative data are presented in Figure 4; because of the small number of decades involved it was not possible to present any statistical information.
In order to obtain such information all decades with an evaporation reduction of 1.0 mm or more were collected for the whole verification period, the results of which are presented in Table 3.

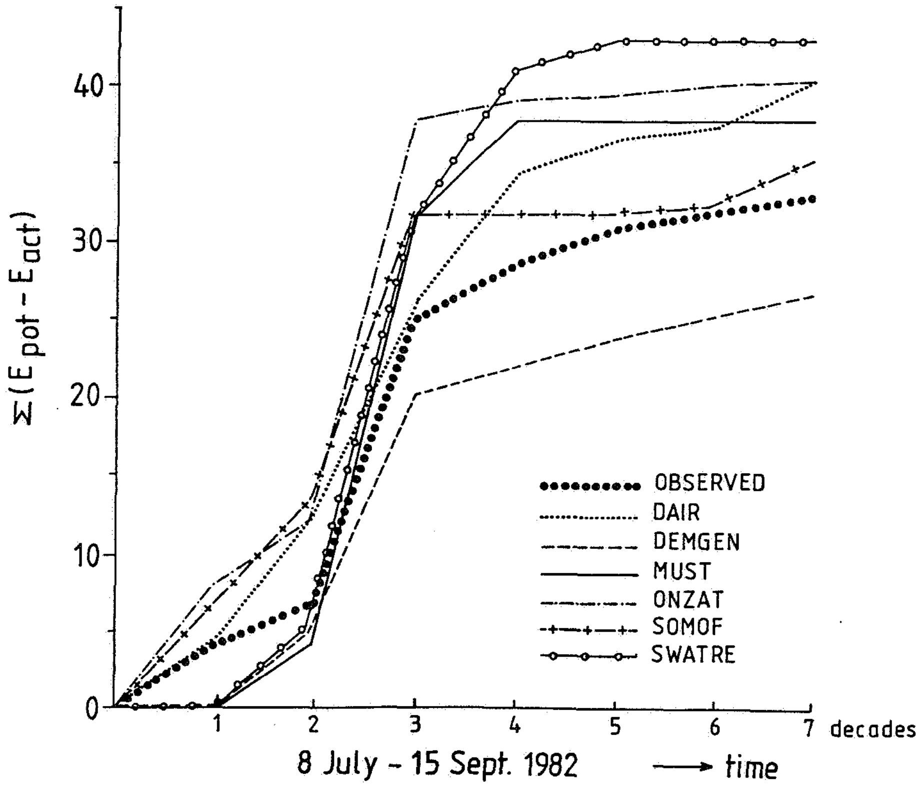



Figure 4. Cumulative ET-deficit versus time for measured and calculated values.

All models compute the flux at the lower boundary of the rootzone which made it possible to keep track of the waterbalance of the rootzone and identify the source of the evaporated water. This could be compared with field data of the moisture content taken with a neutron probe.

It was concluded that all models performed satisfactorily under Dutch climatic conditions, none were significantly better or worse. The pseudo steady state models have the advantage of much greater time steps but are conceptionally more complicated.

Table 3. Actual evaporation 1979-1982. $E_{meas.}$ versus $E_{model}$ and only for decades for which $E_{pot} - E_{meas.} \geq 1.0$ mm.

Actual evapotranspiration 1979-1982

$E_w$ vs $E_m$

decades for which $E_{pot} - E_w \geq 1.0$ mm

$\Sigma E_{pot}$=488.3 $\Sigma E_w$=417.0 $\bar{E}_w$=21,9 s=5.4

$\Sigma E_{pot}$(DAIR)=460.2

| | Demgen | Must | Must 2 | Onzat | Somof | Swatre | Dair |
|---|---|---|---|---|---|---|---|
| $\Sigma E_m$ | 465.2 | 437.3 | 444.4 | 433.9 | 447.9 | 445.2 | 409.9 |
| slope | 0.70 | 0.75 | 0.87 | 1.07 | 0.98 | 0.62 | 0.69 |
| stand. deviation of slope | 0.07 | 0.09 | 0.09 | 0.12 | 0.10 | 0.09 | 0.17 |
| intercept | 4.73 | 4.65 | 1.55 | -2.39 | 1.23 | 7.34 | 1.92 |
| corr.coeff. | 0.92 | 0.89 | 0.92 | 0.91 | 0.92 | 0.86 | 0.78 |
| abs. error % | 0.13 | 0.11 | 0.10 | 0.09 | 0.11 | 0.15 | 0.11 |
| variation coeff. % | 0.18 | 0.14 | 0.12 | 0.11 | 0.12 | 0.19 | 0.14 |

$E_w$ = measured $E_{ACT}$

$E_m$ = model $E_{ACT}$

$\bar{E}_w$ = mean measured $E_{ACT}$ over selected decades

Number of selected decades: 19 (19 x 21.9 = 417 mm)

## 6 Evaluation

DAIR and DEMGEN can only produce results as 10 days totals, hence the results of all models were presented in this way. Although for this particular study the daily output of the remaining models were not analysed it is to be expected that the 10-days summation has caused a certain smoothing of the results.

One important problem concerning one-dimensional column models is with regard to the lower boundary, where the actual value of the hydraulic head is influenced by the upper boundary (ET) as well as by factors regarding the saturated groundwaterflow. In this study measured values of the groundwatertable were used as lower boundary values, sometimes resulting in unrealistic fluxes through the bottom of the one-dimensional column. This is due to the fact that the watertable under fieldconditions often reacts much faster (preferential flow) than one would expect from the model simulations.

Finally the calibration period contained data of an extremely dry year (1976), which means that no extrapolation took place in considering the evaporation deficits for the verification period.

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# THE CALIBRATION AND VERIFICATION OF THE AGROHYDROLOGICAL MODEL DEMGEN IN TWO EXPERIMENTAL AREAS IN THE NETHERLANDS

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**Abstract**

DEMGEN is evaluated on field data, with emphasis on unsaturated flow, drainage and evapotranspiration. DEMGEN comes out as a quite manageable and reliable tool for the simulation of regional water demands, also in comparison with other models. A new method for determination of drainage functions is presented, as well as a graphical tool for schematization of soil physical characteristics for composite and spatially variable soil profiles. Adjustments to DEMGEN are proposed for improving the performance in wet periods, while also attention is paid to soil hysteresis. The main results also apply to other models for unsaturated flow.

## 1 Introduction

DEMGEN (Demand Generator) is the PAWN (Policy Analysis of Water Management for the Netherlands) model for evaluation of water demands in agricultural areas, developed for Rijkswaterstaat by the Rand Corporation (USA) in collaboration with the Delft Hydraulics Laboratory (NL). With agriculture as the major water consumer in the country, DEMGEN is the core of the instruments used in PAWN for the periodical evaluation of water management policies, as published in a national water policy document for the Dutch government every 4-5 years. The present study deals with an extensive test of DEMGEN on field data from two experimental basins (Hupselse Beek and Sleen area) operated by Rijkswaterstaat since ca. 1970. Outside the performance of DEMGEN in dry periods, also that in wet periods is dealt with, in view of the modelling of water quality in PAWN with DEMGEN-related models.

## 2 Brief overview of DEMGEN

A comprehensive description of DEMGEN is given in Abrahamse et al. (1982). DEMGEN simulates hydrological processes for mutually independent computation areas: PLOTS, characterized by land use and a number of physical characteristics. By DEMGEN's time-step stationary nature these characteristics can be represented by a set of functions, of which those relevant to the present study are listed in Table 1a and illustrated in Figure 1. The soil profile is schematized into a single rootzone/subsoil system. The hydrological state of the system is represented by $\gamma$, $\psi$, $\Delta_r$ and $\Delta_s$ (symbols Figure 1). All flows (P, $E_p$, $E_a$, v, D) are constant within time-steps of (normally) ca. 10 days, for which separate rootzone and subsoil water balances are computed. The functions of Table 1a apply to periods with upward capillary rise ($v>0$). In periods of rainfall surplus ($P-E_p$) with $v<0$ (rootzone loss) a simplified scheme is applied: the field capacity concept. This assumes a hydrostatic distribution of the subsoil suction, by which $\psi=\gamma$ (Figure 1). The surplus of $P-E_p$ above the storage-capacity of the rootzone according to $\Delta_r(\psi)$ then is the rootzone loss for the time-step under consideration. For $\gamma>\gamma_m$, $\psi=\gamma_m$ is taken, where $\gamma_m$ (discussed in detail later) may be interpreted as the maximum depth to which the stationary flow concept is considered to be valid in a general sense.

## 3 Experimental basins and field data

The Hupselse Beek area is a gently sloping cover sand area with shallow ground water levels. By the presence of a shallow (2-4 m) impermeable clay layer groundwater interactions to the outside can be neglected. The Sleen area shows a typical succession of small ridges with deep, and valleys with shallow groundwater levels. Geohydrologically the area is an open system with strong groundwater interactions to the outside.

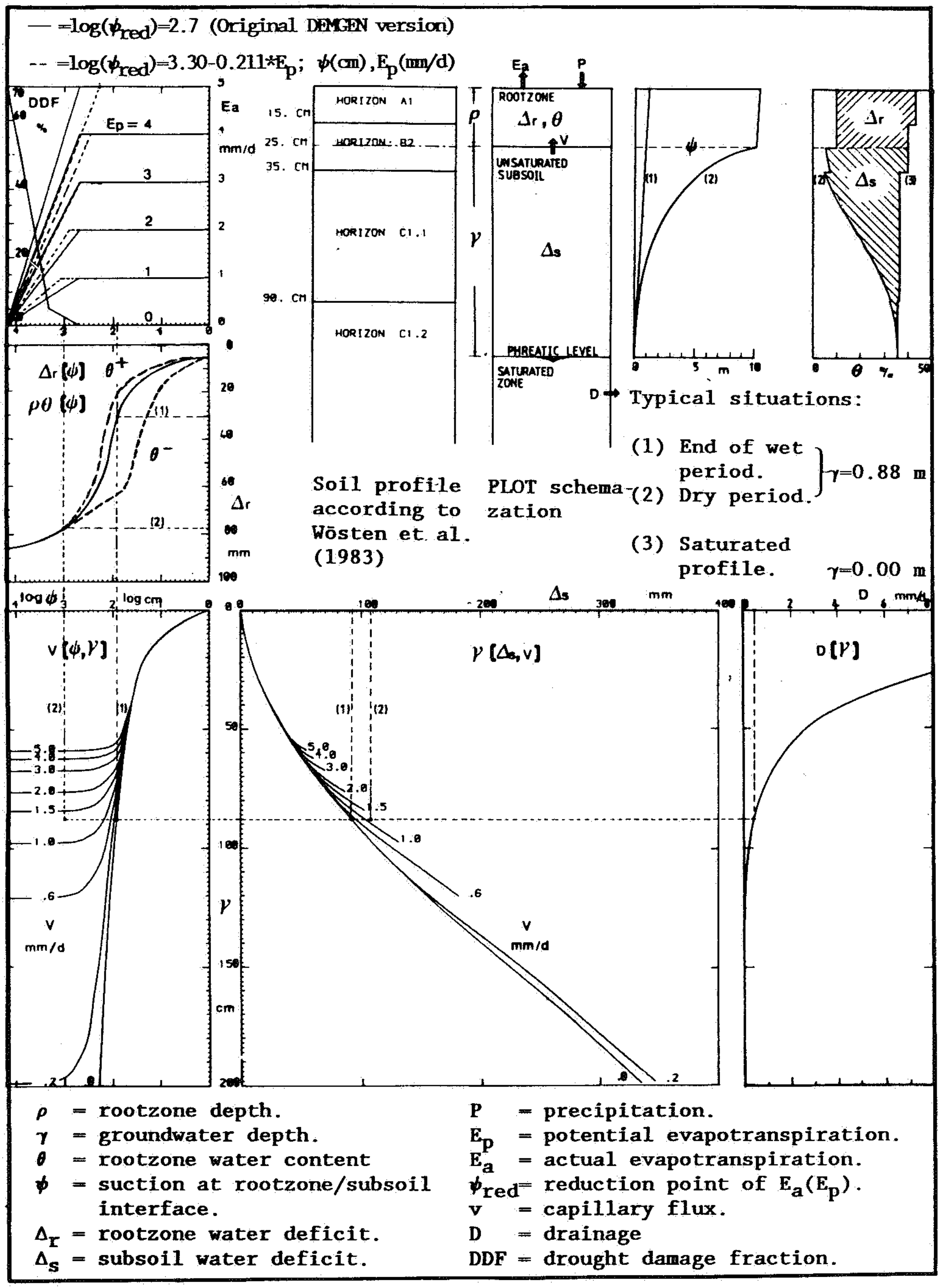


Figure 1. DEMGEN schematization and functions for site 1 (Table 1c).

Further data on the experimental basins are summarized in Table 1b. The main validation variables for the simulations discussed in this paper concern soil water data ($\Delta_r$, $\Delta_s$) for 6 sites in the Hupselse Beek and 11 sites in the Sleen Area, obtained with a neutron depth probe (NEA), an account of which is given in Van Vuuren (1984b). Data on $E_a$ are only available for one site in the Hupselse Beek area (Site 1, Table 1c).

## 4 Performance of DEMGEN and sensitivities

Van Vuuren (1982) shows by means of an areal simulation for the Hupselse Beek that DEMGEN is quite sensitive to the drainage function and the soil physical characteristics used. Van Vuuren (1984a) reports of point-simulations for site 1, in which the partial concepts of DEMGEN could be studied in a more independent way. DEMGEN was used in the reversed way, i.e. by using input-$\gamma$, hence excluding the influence of the drainage function. It followed that the evapotranspiration concept, apart from a slight correction in the reduction point $\psi_{red}$ (Figure 1), performed quite well. Further it was shown that 1) $\gamma_m$ (1 m in the original DEMGEN version) should be at least 2 m for the site in question, and 2) that, in spite of an improved way of determination of the drainage function (next paragraph), $E_a$ was still sensitive to small errors in predicted $\gamma$ with this function. Since then, similar computations were carried out for all 17 neutron probe measurement sites, with quite different soil-hydrological properties. Figure 2 gives some typical examples of simulations for the sites described in Table 1c. The simulations, with 1976-1978 for calibration and 1979-1982 for verification, concern either computations with input-$\gamma$ for determination of $D(\gamma)$ and examination of $\gamma_m$, or computations with input-$D(\gamma)$, for examination of the final simulation results. From the simulations it follows:

1) $\gamma_m$ should be set to a value as large as ca. 5 m for well conducting sandy soils. See the "plateaus" in $\Delta_r$ (Figure 2f) for site 2 due to $\gamma_m$ = 2 m. Note, that $\gamma_m$ controls the flow of water to the subsoil in wet periods. Possibly $\gamma_m$ should be depending on the soil type.
2) $\Delta_r$ is generally predicted quite well in typically dry periods. In other periods, however, strong deviations occur in both $\Delta_r$ and $\Delta_s$.
3) DEMGEN's performance for peaty profiles is still poor (Figure 2g).

4) The improved $D(\gamma)$ still results in small deviations in predicted $\gamma$ (Figure 2e), for which particularly $E_a$ is quite sensitive.

It seems that particularly the problems under 2) and 4) are due to soil hysteresis, which is neglected in DEMGEN. So, at this stage soil hysteresis might be the main remaining source of inaccuracy in DEMGEN, as is supported by the following. When for $\Delta_r(\psi)$ the arbitrary hysteretic trajects indicated in Figure 1 (dashed lines) are introduced in certain periods, the prediction of $\Delta_r$ in wet periods improves considerably (Figure 2b). The apparent state of (constant) adsorption during 1976/77, where the spring of 1978 shows the normal desorption state, might be explained by the fact that the preceeding year 1975 (including the winter of 1975/76) and 1976 both were quite dry years. However, before thinking of modelling hysteresis in DEMGEN, it should be investigated whether the deviations in question average out by aggregation in space.

Table 1. DEMGEN functions, experimental basins and simulation sites.

| Concept | Function | | Basic physical characteristics |
|---|---|---|---|
| Evapotranspiration | $E_a(E_p,\psi,\psi_{red})$ | (Evapotr.function) | Cropfactor f |
| Unsaturated flow | $\Delta_r(\psi)$ | (Rootz.deficit function) | Rootzone soil water ret. curve* |
| | $v(\psi,\gamma)$ | (Cap.rise function) | Subsoil conductivity curve* |
| | $\gamma(\Delta_s,v)$ | (Subs.deficit function) | Subsoil water ret. curve* |
| Drainage | $D(\gamma)$ | (Drainage function) | Calibration on measured $\gamma$ |

* also for composite rootzones and/or subsoils

1a. Summary of physical functions in DEMGEN (Figure 1 for symbols).

| | HUPSELSE BEEK | SLEEN Ridges | SLEEN Valleys |
|---|---|---|---|
| Superficie ($km^2$) | 6.5 | 57 | |
| Soils | sand - clay loam | sand | loamy sand - peat |
| (Sub)soil variability | short distance/random | long distance/map-units | |
| Groundwater depth (m) | 1-3 | 2-10 | 1-2 |
| Land use grass/crop/wood (%) | 72 / 14 / 6 | 35 / 42 / 11 | |
| Time-dep.data | P, $E_p$, $E_a$, $\gamma$, $\Delta_r$, $\Delta_s$, Q | P, $E_0$*, $\gamma$, $\Delta_r$, $\Delta_s$, Q | |

*: open water evaporation; $E_p$ estimated from $f*E_0$ with f=0.7(winter)-0.8(summer)

1b. Data on the experimental basins.

| | | Name | Rootzone | Subsoil | Land use | range $\gamma$ (m) |
|---|---|---|---|---|---|---|
| HUPSELSE BEEK | Site 1 | Assink-pv | Fine sand | Fine sand | Grassland | 0.20-2.00 |
| SLEEN | Site 2 | Staatsbos | Med. fine sand | Fine sand | Woodland | 3.00-5.00 |
| | Site 3 | Electr.mast | Peat | Peat/loam | Grassland | 0.00-0.80 |

1c. Data on the simulation sites.

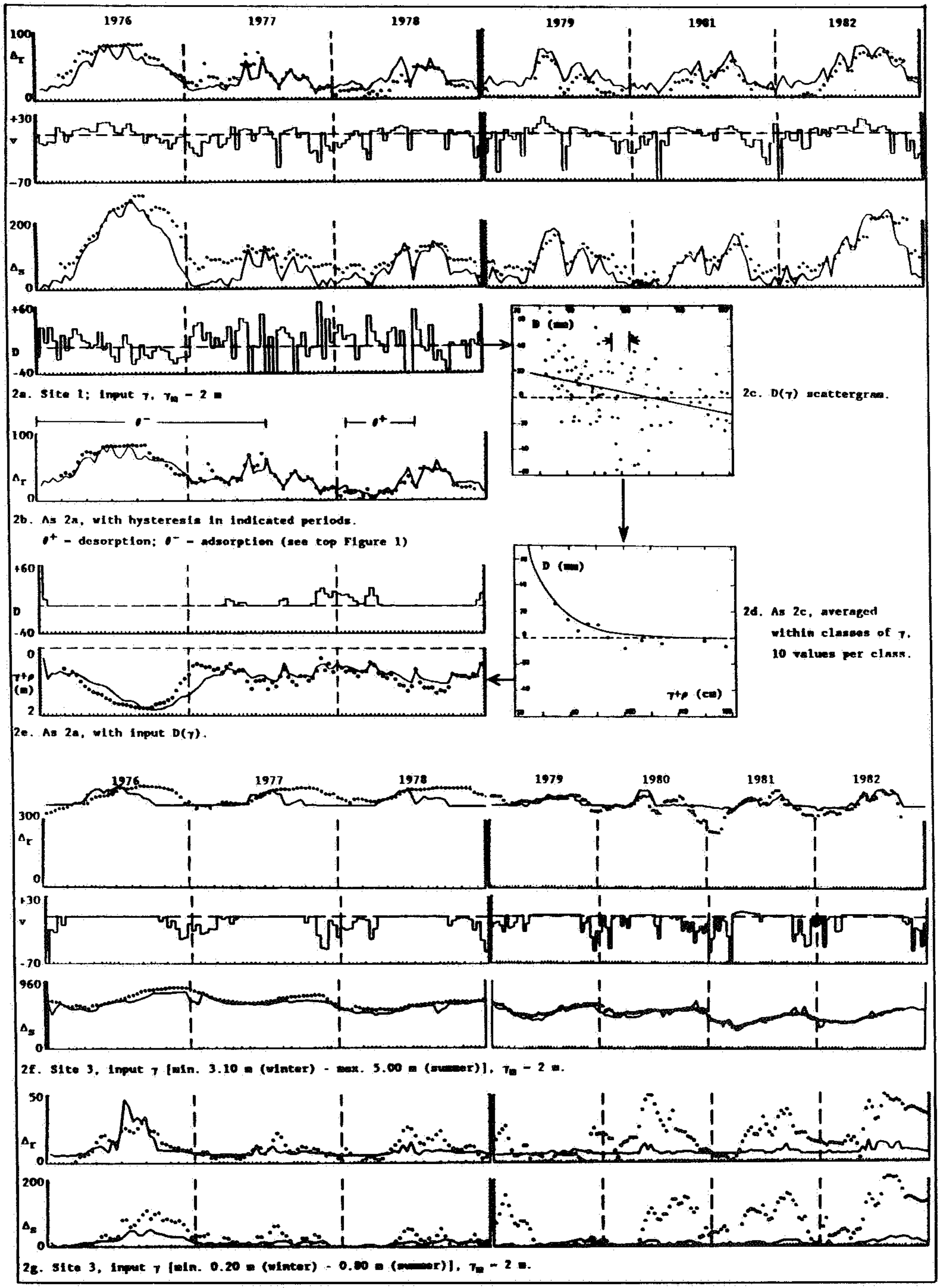


Figure 2. Simulation results. ——— = model; • = measurement.
All variables in mm, unless otherwise indicated.

## 5 Determination of drainage functions

By using DEMGEN in the reversed way, time-step drainage is the result of the subsoil water balance, i.e. $D=\partial\Delta_S/\partial t-v$. For determination of $D(\gamma)$, a scattergram of D (Figure 2a) vs. $\gamma$ (Figure 2e, dots) is constructed (Figure 2c). The wide scatter is then diminished by averaging the data points within classes of $\gamma$, leading to Figure 2d. Van Vuuren (1984a) has shown that this is allowed since the scatter is mainly due to (time-variant) simulation errors in $\Delta_S$ and v. The result is remarkable: where Figure 2c only allows for a straight line to be fitted, Figure 2d permits a function that indeed reflects the physical behaviour of the system. Further experience with this method for the PAWN schematization of the Netherlands, as reported by Grashoff (1987,1988), showed that the steeply inclined traject mostly comes out quite accurately, by which a broken-linear function results as a suitable form for $D(\gamma)$ in practice.

## 6 Schematization of soil characteristics

One of the problems in the regional modelling of water demands is the schematization and aggregation of composite and/or spatially variable soil profiles into workable units. This focusses particularly on the subsoil. For stationary flow conditions the soil physical functions $v(\psi,\gamma)$ and $\gamma(\Delta_S,v)$ provide a basis for this. The functions are derived from the basic soil physical characteristics (Table 1a) by using the formulas for stationary unsaturated flow as given for example in Abrahamse et al. (1982). Figure 1 shows the schematization of a 3-layer subsoil into one model-subsoil, as produced by the computer program FYSKAR, developed at Rijkswaterstaat. Van Vuuren (i.p.) shows how soil physical functions using these graphs are easily compared by defining a certain "window" in terms of the state variables $(\gamma,\psi)$, how the influence of disturbing layers can be traced, and how aggregation in space can be done, all within specified accuracy limits with respect to v and $\Delta_S$. The method was used for establishing an areal PLOT schematization for both experimental basins on the basis of field data from Wösten et al. (1983) and Visschers and Bannink (1986), which, together with computed PLOT groundwater levels, will allow for detailed areal simulations.

## 7 Model comparison and applications in PAWN

Hooghart (1985) gives a report of the comparison of 5 different models by means of simulations for site 1. Though DEMGEN, being the most simple model among them, lacks certain possibilities of the more advanced models, e.g. in predicting non-stationary situations, it came out as one of the most accurate models for prediction of 10-day evapotranspiration and shortages in dry periods. This is mainly due to the easy way of calibration of DEMGEN. The outcomes of the present study resulted in adjustments to DEMGEN for further applications at national level. Moreover, the improved performance of DEMGEN in wet periods has contributed considerably to the development of the model DEMNIP, Ruygh et. al (1990), for nitrate and phosphate flows in agricultural areas.

## 8 Conclusions

Given its original purposes, and with adjustments to the unsaturated flow concept and the drainage function as proposed in this paper, DEMGEN performs quite well for practically all hydrological situations present in the Netherlands, except for peat soils. Among other models for the assessment of water demands DEMGEN combines easy manageability with a fairly high degree of prediction accuracy. The adjustments mentioned above also contributed considerably to the modelling of substance flows in the Netherlands with a DEMGEN-based model. The results of the present study also apply to other models for unsaturated flow. Soil hysteresis seems to be the main remaining source of inaccuracy in DEMGEN at single site level, though errors due to this might still average out in space. The last can also be stated for the remaining inaccuracy in the prediction of groundwater levels with the improved drainage function, for which particularly crop evapotranspiration is sensitive. These aspects, as also the prediction of areal discharge by DEMGEN, can be studied in areal simulations for the Hupselse Beek and Sleen area. The areal schematization available for this is also suitable for other models. FYSKAR-graphs based on DEMGEN soil physical functions are a handy tool in schematizating and aggregating composite and spatially variable soils and can be valuable for the regional modelling of water demand.

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# HYDROLOGIC PROCESSES IN SMALL EXPERIMENTAL AREAS INFLUENCED BY VEGETATION COVER

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Abstract

In recent years the vegetation cover is additionally subjected to increasing changes caused by the world's economy. These variations influence hydrologic processes as formation of runoff components and moisture storage and a variety of connected processes. Experimental work in test and representative basins and the application of mathematical models are especially suited to investigate these relations. Results of such investigations concerning the influence of vegetation on soil moisture and the formation of runoff components are presented.

## 1 Introduction

Nowadays the problem characterized by the influence of vegetation on hydrologic processes gains an increasing importance. This question becomes more and more critical because the mankind is strongly confronted with intended or unintentional changes of land utilization.
Alterations are induced by management measures as conversion from arable land into meadow or vice versa, irrigation and drainage of fields, the replacement of single-crop farming by crop rotations, the deforestation or afforestation. Unintentional changes in the vegetation result from forest damages caused by pollutants, or from shifting of vegetation zones due to climatic changes caused by human impact.

Such utilization variations influence the system atmosphere-land surface-soil in all parts. They modify in particular:

- the radiation, humidity balance and carbon dioxide balance of the atmosphere producing climatic changes in a global scale;
- the pollution of sites and areas and as a result the atmospheric pollutant input into waters and soil;
- the amount of the single runoff components and their relative part in total runoff as well as matter transport by the different runoff components (erosion, transport of pollutants and nutrients to groundwater and surface water);
- the amount of stored soil moisture, the moisture-influenced thermal soil properties and thus a variety of biological and chemical soil processes dependent on moisture and temperature;
- whole ecosystems including all before-mentioned influences.

Hence it follows that we are interested in the hydrologic processes of soil water balance and formation of runoff components which are strongly influenced by vegetation. Experimental investigations in test and representative basins and simulations, based on mathematical models of these processes, are especially suited to this research.

## 2 The soil moisture influenced by crop

A plant stand generates two general processes:

a) the interception decreasing the moisture input into the soil;

b) the transpiration increasing the moisture extraction from the soil.

In total we expect, that the soil moisture under a plant canopy is lower compared to bare soil. However, it is to take into consideration, that during the early stage of the crop both processes are not very effective because of the small cover degree and root development. A crop also causes processes counteracting to a) and b):

c) the covering of the soil decreases the energy input and therefore the evaporation;

d) the lower wind velocity and higher air humidity diminish the ventilation-humidity-complex, and therefore the evaporation;

e) the smaller root density in the earlier stages of plant development causes an evaporation higher than transpiration.

If you compare the processes of a) and b) with those of c) and d), you have to expect that the supposed soil moisture deficit increases under the plant canopy in comparison to bare soil according to the phenological development.

This relation was experimentally proved at the agrometeoroligical station Tharandt. Figure 1 shows the temporal development of soil moisture during the vegetation period in a winter wheat crop compared to moisture in bare soil of the same hydraulic properties. Until mid May the soil moisture in the crop is higher due to the processes of c), d) and e). Only after this time the expected soil moisture deficit becomes evident as consequence of the processes a) and b).

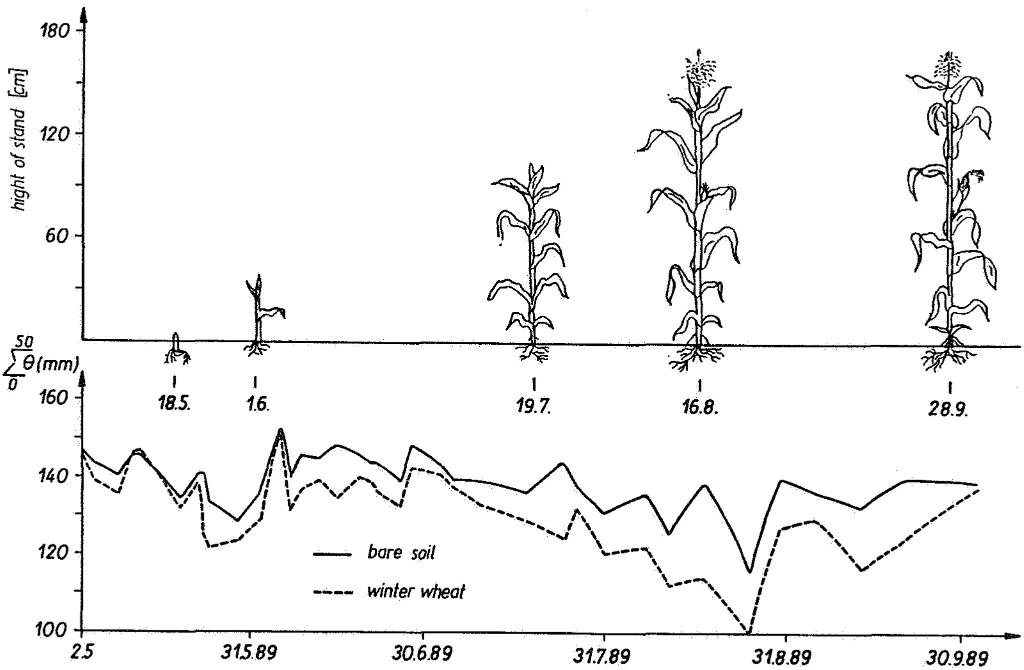


Figure 1. Increasing soil moisture deficit under winter wheat compared to bare soil

## 3 The influence of vegetation on runoff

From investigations on the infiltration process (Peschke,1985, Peschke, 1987) it is known that, beside the storage properties discussed above, the relation PI/k (PI-rain intensity, k saturated hydraulic conductivity) in particular determines the relation of surface runoff to the amount of infiltrated water. Both quantities of this relation are significantly influenced by vegetation. Dense, well developed vegetation decreases the rain intensity on the one side. On the other side the root formation loosens the top-soil, creates additional macropores and increases the hydraulic conductivity. Especially in the forest the upper humus horizon forms a layer with a porosity up to 90 % mainly consisting of macropores which can receive even highest intensities of water supply. Summarizing all details you may expect a lower surface runoff in plant canopies and an increasing amount of infiltrated water which is available for more evapotranspiration and for interflow processes. This in small forested basins experimentally confirmed fact will be examined in the next Sections by the help of models.

## 4 The process-related soil water balance model BOWAM

Based on intense experimental and theoretical investigations the dynamic model BOWAM of the soil water balance was developed (Peschke et al., 1986). It describes all essential processes in the system soil-plant-atmosphere and is a physically based model using simplified analytical solutions of the corresponding differential equations. The model allows the simulation of the following subsystems and processes:

- interception;
- snow cover development and melting as well as a reduction of the hydraulic conductivity during periods of frozen soil;
- infiltration which is subdivided into a saturation phase, recharging soil moisture, and into a following recession phase, during which overland flow is formed;
- the formation of interflow at boundaries of soil layers with different hydraulic properties;
- the flow in macropores;

- deep percolation and groundwater recharge;
- moisture extraction by evapotranspiration;
- the soil moisture content in the different soil layers.

One of the greatest advantages of the model is the use of physically proved parameters derivable from properties of the system soil-plant-atmosphere.

## 5 Application and discussion of the results

With the model, soil moisture, runoff and evapotranspiration were simulated during a period of several years. For the meadow covered test area measured soil moisture data are available. On the other test area managed by a regular crop rotation, beside soil moisture, drainage flow and groundwater level were measured. The parameters were estimated by measurements in the laboratory and during the field work by using of expert's experience.

They were not adapted to the simulation results. The results confirm the theoretical expectation and are well corresponding to the experimental data (Gurtz, 1988).

In order to investigate the influence of the vegetation on the hydrologic processes the first test area was presumed to be covered by different crops during the summer half year 1983. The various vegetation influences were described by parameters such as the storage capacity of the interception, the degree of vegetation cover, the albedo, the root depth and distribution. Figures 2 and 3 show the results.

In Table 1 the following abbreviations are used: P-precipitation, EP-potential evapotranspiration, ER-real evapotranspiration, EI-interception, PEFF-effective rainfall, FBMP-flow in macropores, FH-interflow, FBN-deep percolation, SB-Soil moisture changing in the considered period.

Table 1. The water balance for the test area in the summer of 1983, data in mm

| P = 407 | EP | ER | EI | PEFF | FBMP | FH | FBN | SB |
|---|---|---|---|---|---|---|---|---|
| bare soil | 478 | 307 | 0 | 23 | 18 | 10 | 98 | -49 |
| meadow | 524 | 361 | 96 | 14 | 15 | 8 | 78 | -70 |
| winter rye | 523 | 360 | 59 | 9 | 14 | 16 | 64 | -58 |
| forest | 653 | 453 | 137 | 5 | 12 | 7 | 40 | -111 |

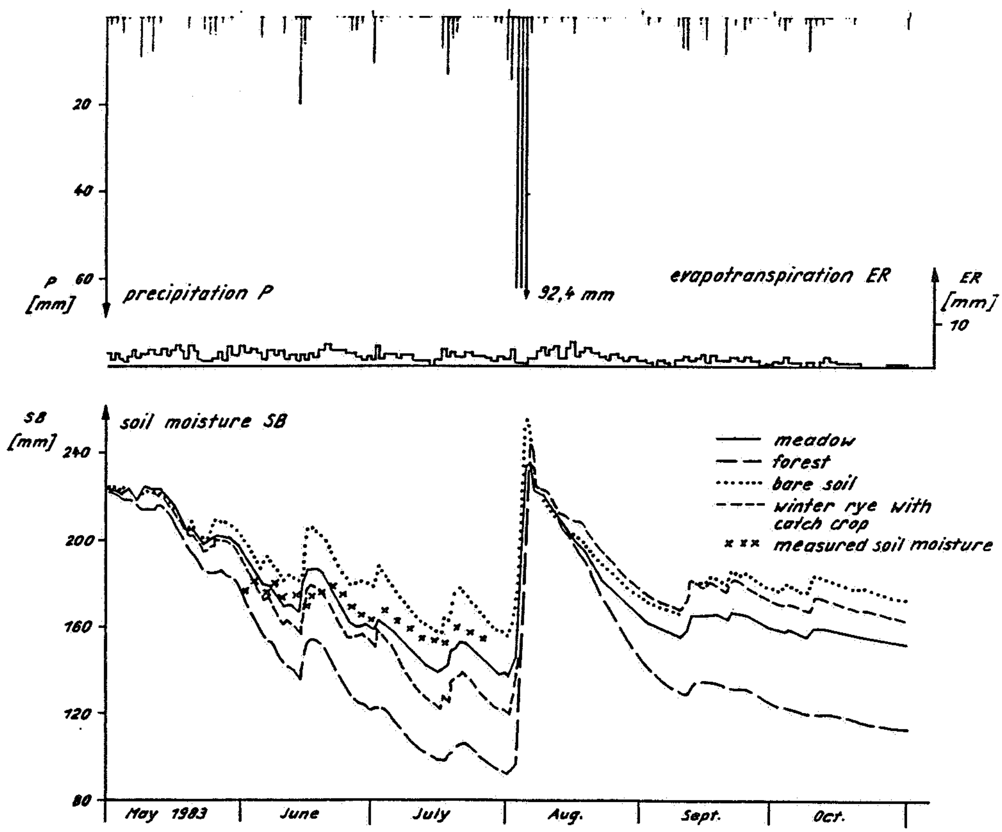


Figure 2. Soil water balance of the test area simulated by BOWAN

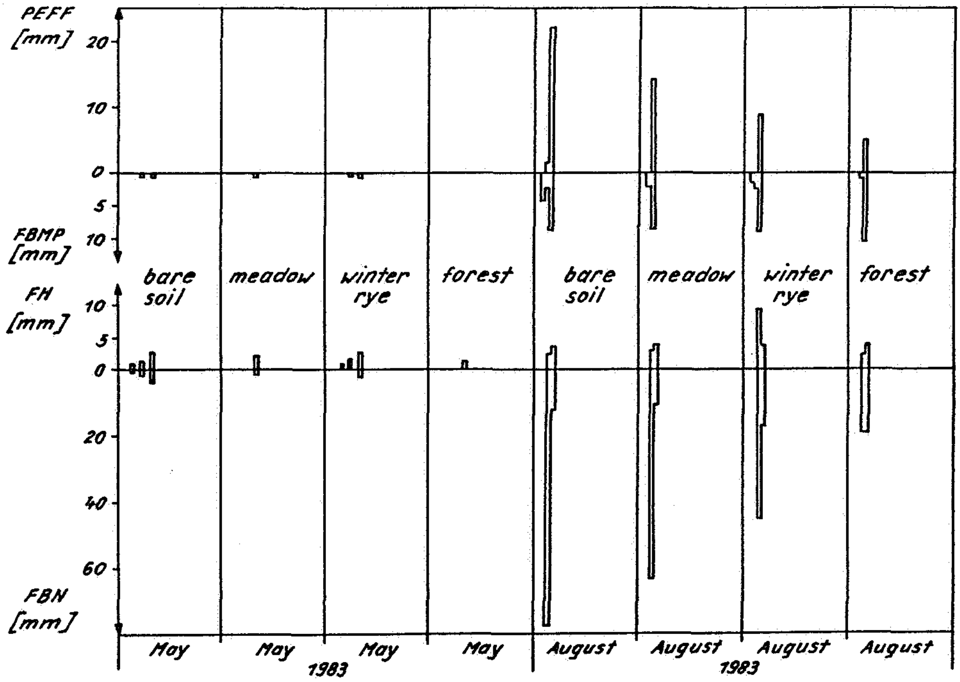


Figure 3. Formation of the runoff components during May and August 1983 for different crops

The results show that winter rye and meadow have similar real evapotranspiration despite different interception. However, they differ in the various runoff components, mainly caused by different vertical moisture extraction from the soil. The varying amount of effective rain during the storm event in the beginning of August is determined by the different preceding soil moisture. The increasing moisture extraction due to stronger root formation diminishes the deep percolation.

The forest and the bare soil yield extreme deviations, concerning the runoff components and soil moisture, from the results for winter rye and meadow (Fig. 3). Comparison of the temporal soil moisture development between winter rye and bare soil shows the same pattern, as discussed in Section 2. From mid September the growing influence of the intercrop can be seen.

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# EXPERIMENTAL STUDY OF TRANSPIRATION IN MOUNTAINOUS RESEARCH BASIN

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## Abstract

The role of actual evapotranspiration in the water balance of mountainous basins calls for more attention and requires better understanding of the transpiration processes. The paper should contribute to the determination of the actual evapotranspiration taking into account the vegetation characteristics, orography (Figures 2, 3) and also measurements of the supplementary meteorological data and transpiration (Figure 4). Finally, relationships between transpiration and forest surface temperature (Figure 5) were analyzed and replaced by two exponential relationships between transpiration and air temperature 1.5 m above the forest canopy for eastern and western orientation of the basin slopes (Figure 6).

## 1 Introduction

Specific features of mountainous areas and their considerable structural complexity require also a specific approach to different elements of the water balance. Complicated conditions in mountainous basins often reduce the water balance computations to counting differences between the two directly measurable components: precipitation and runoff. Resulting amount of water is mainly composed of the evapotranspiration and infiltration. And therefore, the problem of more accurate computation of the water balance has led to the determination of rather easy computed and more evenly distributed component of evapotranspiration. However, determination of the actual evapotranspiration which heavily depends on vegetation, requires a detailed physical description of the transpiration processes. The experimental study of transpiration in mountainous research basins should contribute to the spatial distribution of the actual evapotranspiration considering vegetation within the basin and the elevation, steepness and orientation of its slopes. The point measurements of transpiration have been carried out on the representative plots and selected trees. For the areal extrapolation the additional measurements of surface temperature were done by remote sensing infrared techniques utilizing the opposite slopes exposure in the basin.

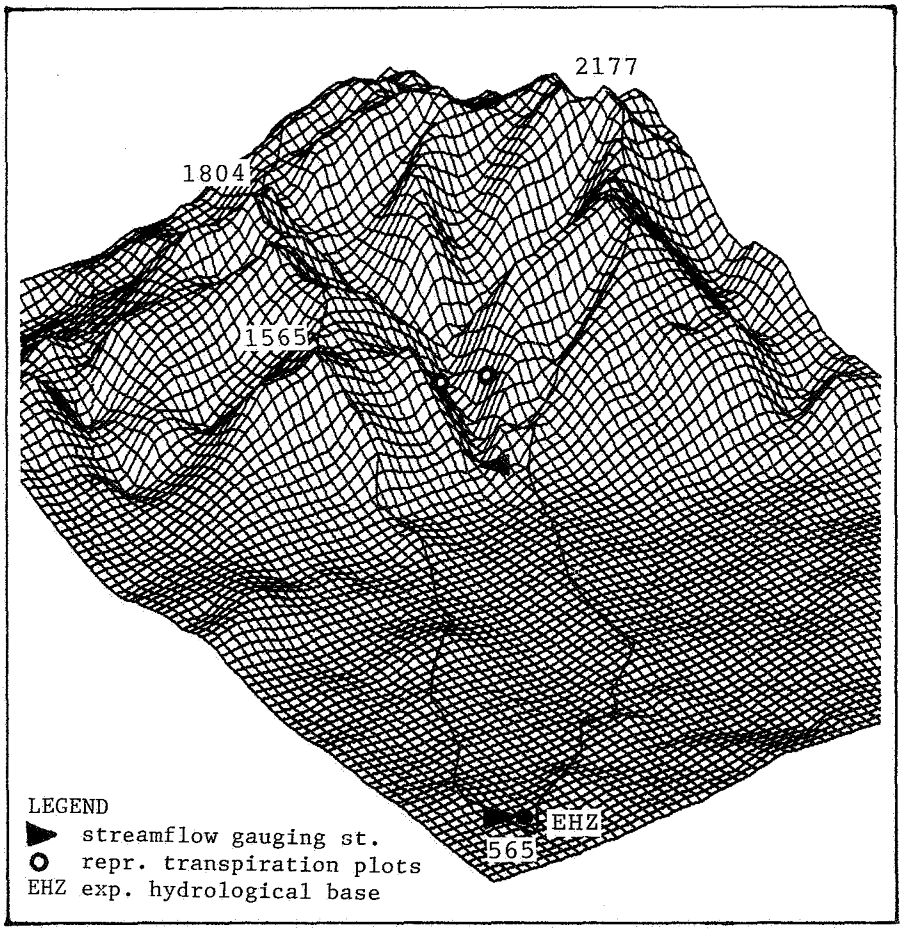


**Figure 1** The experimental research basin Jalovecký potok

## 2 Study area

The subject study is based on data collected in a mountainous research basin (23 km², 800-2177 m a.s.l.) in Western Tatras (Figure 1) covered by spruce forest (65%), dwarf pines and alpine grass (35%). The direct measurements of transpiration were done on selected spruce trees (app. 40 m high) within the two representative transpiration plots located on eastern and western slopes of the research basin at the altitude 1160 m a.s.l. The transpiration plots were also equipped with instruments for measurement of air temperature (2 m above the ground, 0.5 and 1.5 m above the canopy), humidity (0.5 m above the canopy) and wind speed (0.5 and 1.5 m above the canopy). The whole area of the experimental basin is 46 km² with the unforested foreland (23 km², 565-800 m. a.s.l) used for agriculture. Subdivision of the basin on mountainous and foreland parts allows to determine the water balance elements with much higher accuracy.

## 3 Data collection system

For the measurement of transpiration the heat balance method by Čermák et al. (1973, 1982) and Kučera et al. (1977) was used and modified for mountainous conditions by Rášo (1989). The direct measurement of sap flow through the active xylem of selected representative tree trunks was done by needle thermometers (2 sets, 8 sensors each for one measured tree), heated by electrodes (2 sets, 5 electrodes each). The automatic recorder is than registering differences in temperature of the heated and unheated row of thermometers. The obtained differences $\Delta$ T are indirectly related to the speed of sap flow which is finally used for calculation of the intensity of transpiration.

All supplementary meteorological data as the air temperature and humidity, wind speed and radiation are recorded at standard hights (see above) and at the typical 40 m high spruce canopy.

Mutually visible representative transpiration plots 100 by 100 m (Sokol - eastern slope, Trnác - western slope) allow easy use of the infrared thermometer RAYNGER II. The simultaneous areal measurement of surface temperature were carried out in the spectrum range 8-14 or

10.5-12.5 μm and the emissivity coefficient equals 0.97.

## 4 Transpiration measurements

Results of transpiration measurements carried out on the same tree significantly vary in time depending on the soil moisture, sunshine, temperature and humidity of air, and wind speed. Variability of daily volumes transpirated by selected spruce trees was 8 to 60 l per day. Lack of data on soil moisture, especially in steep mountainous areas, calls for more attention to easy measurable and rather evenly distributed meteorological data. However, limiting role of the soil moisture in arid or semi-arid areas should be foreseen and taken into account. Spatial variation of transpiration considerably depends on the areal characteristics of the vegetational canopy (type, age and health of forest) and orography of the basin. Especially, the exposure of mountain slopes to the solar radiation is influencing the diurnal course of transpiration (Figure 2). Fortunately, this influence can be determined for each stand and actual horizon and regularly calculated (Figure 3).

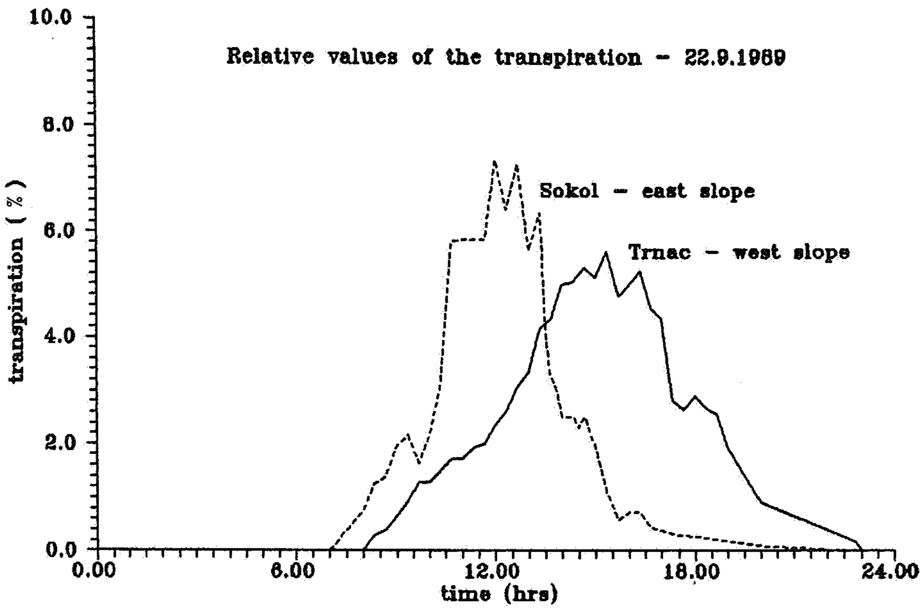


Figure 2 Comparison of the diurnal course of transpiration for eastern and western slopes

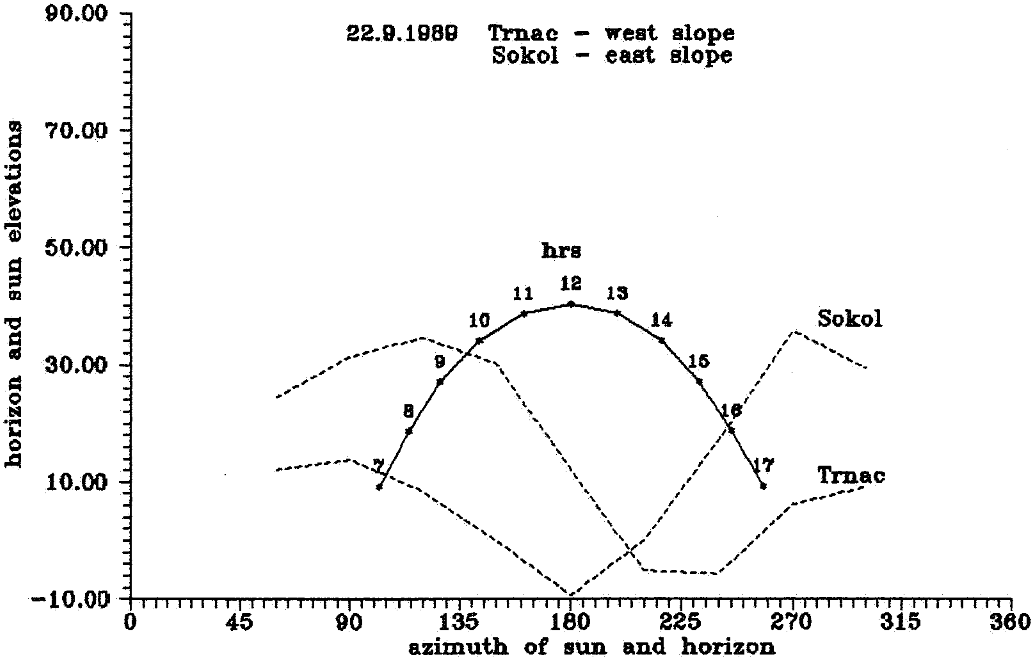


Figure 3 Sun elevations and terrain horizons for both representative transpiration plots

## 5 Relationship between transpiration and temperature

Close relation between transpiration and temperature in shown on Figure 4. As an example we have presented the relations of transpiration measured on the western slope (Trnác, 22.7.1989) to the surface temperature (dashed line) and to the air temperature 1.5 m above the forest canopy (dashed line). Similar results were obtained for both locations Trnác and Sokol. However, more detailed statistical analysis is required.

### 5.1 Transpiration and surface temperature

Transpiration and surface temperature is expected to be closely related. Figure 5 shows two rather different exponential relationships for measured transpiration and surface temperature on Trnác and Sokol representative plots. This result indicated the reason why various remote sensing methods (infrared photometry) have not proved to be as successful as presumed. Anyhow, doubtless significance of the infrared photometry remains in use of this method for areal extrapolation of single tree transpiration measurements. Of course, a wider utilization of any remote sensing method is limited by usual discontinuity of the monitoring. The same problem was avoided in the subject study by using data on air temperature 1.5 m above the forest canopy.

## 5.2 Transpiration and air temperature

Transpiration and air temperature have rather close exponential relationships for both locations (Figure 6). Figure 6 shows the subject relationship for western slope orientation (dashed line) by Equation 1

$$TR_w = 0.008226 \exp (0.294644 \, T_{1.5}) \quad (1)$$

where

$TR_w$ = transpiration (West) in $1.hrs^{-1}$

$T_{1.5}$ = air temperature 1.5 m above the canopy in °C

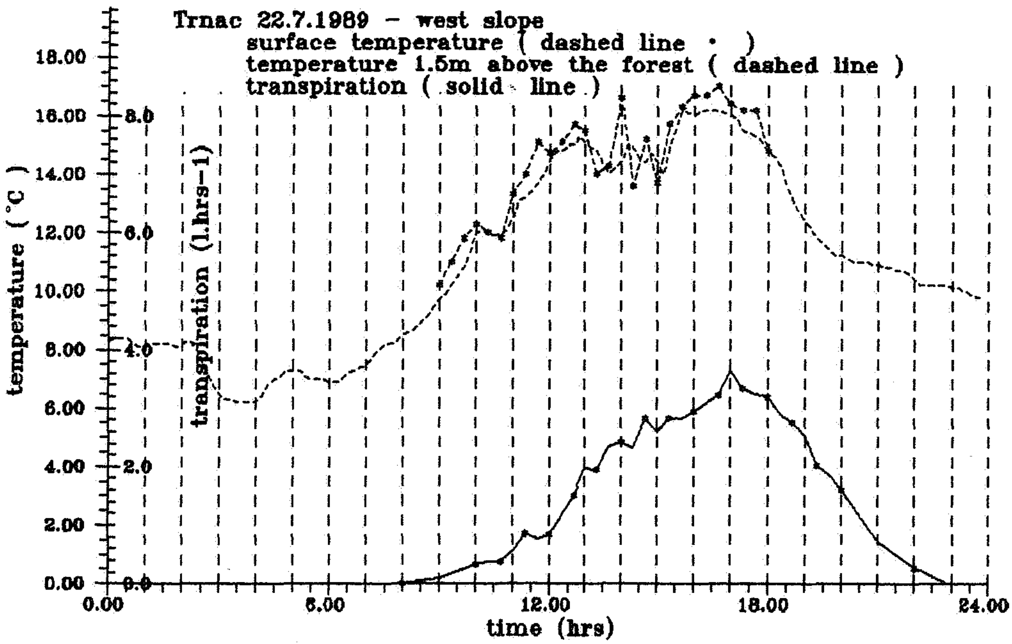


Figure 4 Relationship between the air, surface temperature and transpiration on western slope Trnác

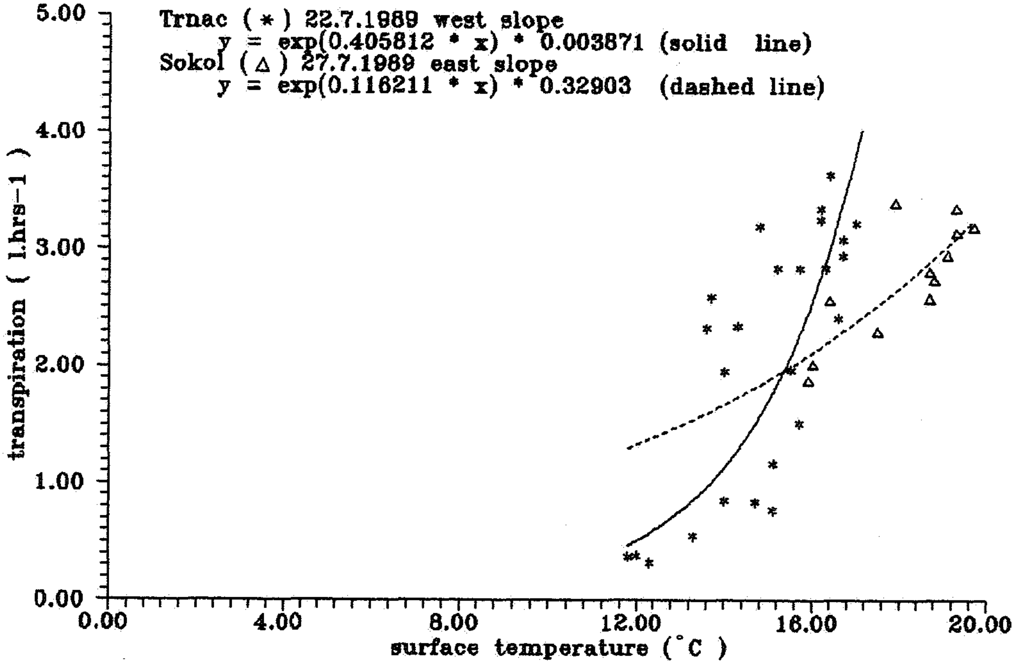


Figure 5 Comparison of the surface temperature and transpiration for both representative plots

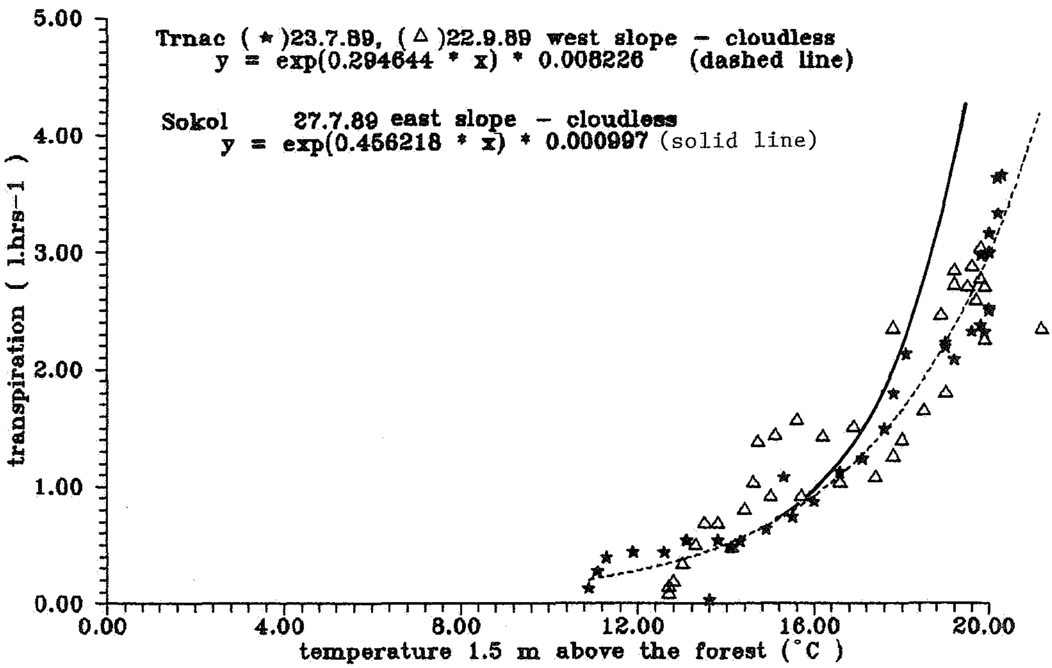


Figure 6 Comparison of the air temperature 1.5 m above the forest and transpiration for both representative plots

Equation 2 is valid for eastern slope orientation (solid line)

$$TR_E = 0.000997 \exp (0.456218\ T_{1.5}) \qquad (2)$$

where

$TR_E$ = transpiration (East) in $l.hrs^{-1}$

$T_{1.5}$ = air temperature 1.5 m above the canopy in °C

The above mentioned equations are a useful tool for an estimation of transpiration through the typical spruce forest in mountainous areas based on easily measurable air temperature. The presented study has contributed to the determination of actual evapotranspiration and precision of the water balance of mountainous basins in the Western Tatras by Molnár et al. (1988).

## Acknowledgements

The authors gratefully acknowledge the assistance of many members of the staff of the Institute of Hydrology and Hydraulics of the SAS in Bratislava, particularly of those contributing to the field measurements in hard mountainous conditions of the Experimental Base at Western Tatras.

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# FLOOD GENESIS IN A SMALL FORESTED WATERSHED LOCATED ON THE SOUTHERN SLOPES OF THE MASSIF CENTRAL (FRANCE)

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Abstract

Flood genesis is studied in a small forested drainage basin situated on the southern face of the Mont-Lozère (France). Studies show the existence of a threshold beyond which the water in the river rises suddenly and quickly, passing in a few hours from 0,3 $m^3/s/km^2$ to 1 and perhaps 2 $m^3/s/km^2$, if the rain does not stop.

This threshold corresponds to about 270 mm for water storage of the basin (sum of groundwater and soil storage).

The amount of rain needed to reach this threshold varies in this study from 44 mm to 216 mm, depending on the amount of this storage at the beginning of the rainfall event.

This observation allows us to interprete the flood runoff as the result of overflowing of temporary water tables, which saturates large parts of the basin. Under such conditions, the role of vegetal cover appears to be of secondary importance.

Résumé

L'étude des conditions d'apparition d'une grosse crue, dans un petit bassin-versant forestier situé sur le flanc Sud du Mont-Lozère (Massif

Central, France), permet de mettre en évidence l'existence d'un seuil, à partir duquel la montée de crue est dans tous les cas brusque et importante, l'écoulement passant en quelques heures de valeurs de l'ordre de 60 l/s (300 l/s/km²) à celles de 200 et 300 l/s (1 à 1,5 m³/s/km²) pour autant que la pluie continue, pouvant même atteindre 400 l/s.

Ce seuil dont la valeur peut être exprimée en lame d'eau équivalente, correspond au stock hydrique du bassin, défini comme l'ensemble des réserves hydrique et hydrologique ; sa valeur dans l'exemple étudié ici est estimée à 270 mm. Suivant l'état des réserves en début d'épisode pluvieux, la hauteur de précipitation nécessaire pour atteindre ce seuil donc pour provoquer une crue, varie, dans les cas considérés ici, de 44 à 216 mm.

Ces observations permettent d'interpréter l'écoulement de crue comme étant produit par un débordement très généralisé de nappes temporaires, s'ajoutant à la nappe de fond de vallon et saturant une grande partie du bassin-versant. Dans ces conditions, le rôle joué par la végétation paraît peu important.

## 1 Introduction

Located in the South of the Massif Central (France), the Cevennes mountains face the Mediterranean raining winds. In autumn, intensive storms (more than 400 mm in 48 hours in November 1982 at Pont-de-Montvert) generate high volume of storm runoff and provoke intensive, rapid and destructive floods.
The conditions of appearance of such storm floods are being monitored and studied in a small experimental watershed, located on the southern slope of the Mont-Lozère.

## 2 Site environment and monitoring equipment

The Latte river catchment is one of the three experimental watershed equiped for the study of the influence of vegetal cover on the chemical budgets and on the water balance (Fig. 1). This small catchment (20 ha), is covered with a 60 years old spruce plantation forest (Picea excelsa). The bedrock, an homogenous porphyric granite, is covered by porous, sandy, weakly weathered soils, ranging in depth from 0 to 1 m. The temperature varies between -6° and +18° (LELONG, 1987), and the annual average rainfall reaches 1900 mm (DIDON, 1985).

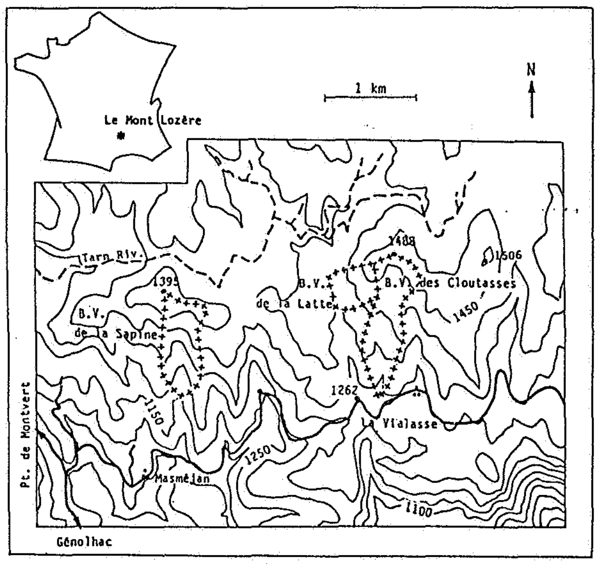


Fig.1 : The Mont Lozère expérimental catchments
(from the 1/50000° map of Génolhac)

The rainfall distribution is measured by a network of five recording raingauges located in and around the studied watershed. Streamflow is recorded at the mouth of the watershed with a specially-designed componend weir with a V-notch at the base. Within the last eight years of field collection (1981-1988) seven major rainfall events (more than 150 mm) occurred during autumn, six of them having generated floods.

## 3 Water pattern characteristics

Some particularities of the water pattern had already been observed by previous studies.

* Rainfall simulations had pointed out the high infiltration capacity of the soils. Under such conditions a HORTON-type overland flow cannot occur on large parts of the basin (COSANDEY, BOUDJEMLINE, ROOSE et LELONG, 1990).

* Floods are always linked with high rainfall events, though amounts of precipitation may vary a lot, (from 44 mm, october 10, 1987, fig. 8 to 241 mm, october 4, 1987, fig. 7), in relation with the water storage in the watershed.

* Flood rise is always sudden and time to peakflow is short, giving evidence of sudden changes in the water pathways and of occurrence of a generalized overland flow. Discharge increases in a few hours 0.3 $m^3/s/km^2$ to one, and perhaps two $m^3/s/km^2$ when the rain does not stop. The storm runoff coefficient exceeds sometimes 50 percent (COSANDEY, 1990).

These studies, combined with field observations, suggested that the storm flows are generated by sudden and significant overland flow which can occur when wide parts of the basin are saturated, according to the "contributing areas" concept (DUNNE and BLACK, 1970). When a threshold corresponding to a maximum value for the groundwater storage is reached, the watertable rises to the surface of the soil and "overflows", inducing a high volume of storm runoff. The aim of this paper is to show how this threshold was determined.

## 4 Determining the threshold for flood rise

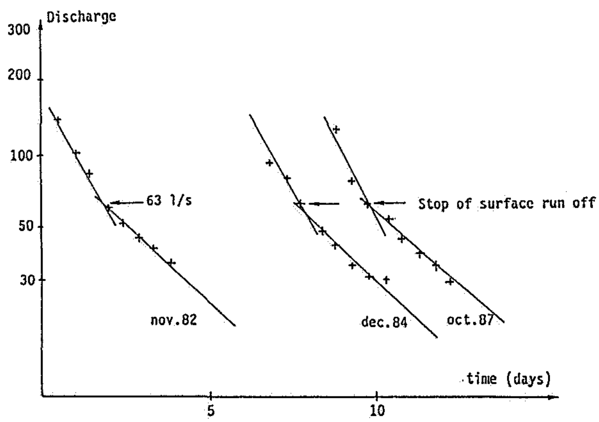


Fig. 2 Evolution of discharge during recessing periods

The figure 2 shows a break in the recession limbs at the value of 63 l/s. This break clearly indicates an important modification in the water pathway pattern within the basin, when a rapid surface runoff decreases to a slower subsurface runoff. According to Maillet's Law (CASTANY, 1963),

63 l/s corresponds, for the groundwater storage, to a value of about 170 mm. It seems therefore possible to admit that this value represents the maximum storage capacity of the soil, and that, above this threshold, the watertable "overflows" ; all the rain falling on these saturated surfaces participates to the storm flow either as an overland flow running over the soil surface, or as a "piston-flow".
Consequently, the 63 l/s value for discharge is assessed to be the threshold for the beginning of the flood.
Under such conditions, significant stormflows cannot occur before he groundwater storage reaches the threshold of 170 mm. However, the rain water can infiltrate through the soil and restore the watertable only after the soil has reached his field capacity. Previous studies, based on field observation (DURAND, 1989) and modelling approach (GUERIN 1987) showed that this field capacity is here of about 100 mm.
So, the value for the total water storage of the basin before flood rise may be assumed to be : 170 + 100 = 270 mm.
Comparisons between computed and monitored values for the amount of rain necessary to induce a flood have been realized in order to assertain this hypothesis.

## 5 Results

The amount of rain necessary to reach the 270 mm threshold - thus to generate a flood - is computed as the simple difference between 270 mm and the value of the total water storage in the basin at the beginning of the rain event. The total water storage is the sum of groundwater storage (according to Maillet's Law, in relation with the baseflow) and soil water storage (computed by the water balance).
Seven storm events (rain >150 mm) occurred during the 8 years of the field studies. Six of them have been recorded and are analyzed below. Five of them produced floods :

5.1 November 7-9, 1982 (Fig. 3)

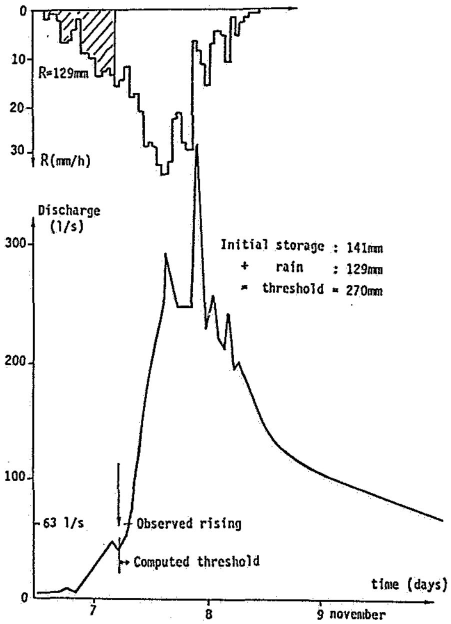


Fig.3 Flood from november 7-9, 1982

- Soil water storage = 90 mm.
- Base-flow = 6.8 l/s, reflecting a 51 mm groundwater storage.

According to previously assumed calculations, with a total water storage of (90 + 51 =) 141 mm, a (270 -141 =) 129 mm precipitation is needed to generate a flood.

According to the rainfall measurements, this value was reached the 7th at 3.00 p.m., and the rise of the flood began at 6.00 p.m., after 170 mm rain.

5.2 December 1-2, 1984 (Fig. 4)

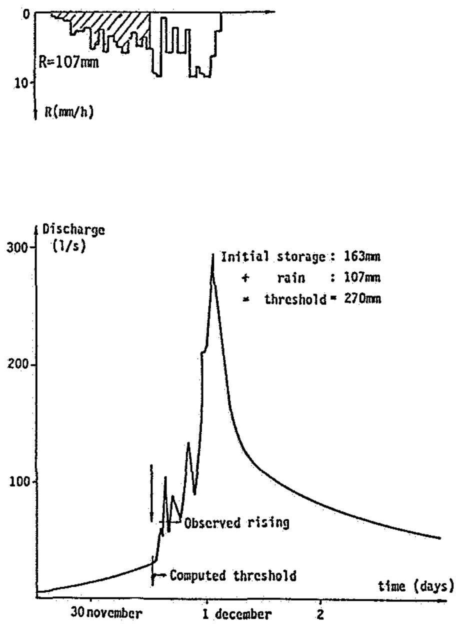


Fig.4 Flood from december 1-2,1984

- Soil water storage = 100 mm.
- Base-flow = 9.5 l/s, reflecting a 63 mm groundwater storage.

According to previously assumed calculations, with a total water storage of (90 + 51 =) 141 mm, a 270 -141 =) 129 mm precipitation is needed to generate a flood.

According to the rainfall measurements, this value was reached on the 1st of December at 1.00 a.m., and the rise of the flood began at 3.30 a.m., after 133 mm rain.

## 5.3 October 13-15, 1986 (Fig. 5)

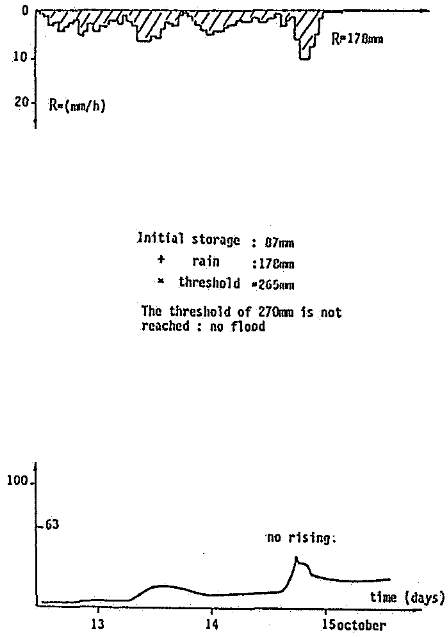


Fig.5 "No flood" from october 13-15,1986

- Soil water storage = 60 mm.
- Base-flow = 2.3 l/s, reflecting a 27 mm groundwater storage.

According to previously assumed calculations, with a total water storage of (60 + 27 =) 87 mm, a (270 -87 =) 183 mm precipitation is needed to generate a flood.

According to the rainfall measurements, this value was not reached. The amount of accurate rain was only 178 mm, and no flood occurred.

## 5.4 November 13-15, 1986 (Fig. 6)

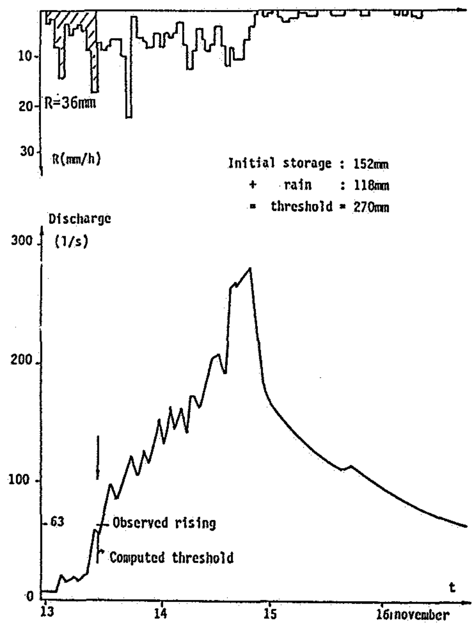


Fig : 6 Flood from november 13-15,1986

- Soil water storage = 90 mm.
- Base-flow = 9 l/s, reflecting a 62 mm groundwater storage.

According to previously assumed calculations, with a total water storage of (90 + 62 =) 152 mm, a (270 -152 =) 118 mm precipitation is needed to generate a flood.

According to the rainfall measurements, this value was reached the 13th at 10.3 a.m., and the rise of the flood began at 12.00 a.m., after 136 mm rain.

## 5.5 October 4-6, 1986 (Fig. 7)

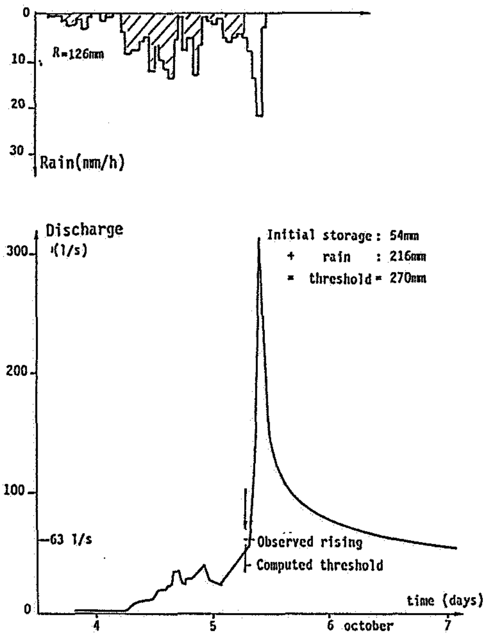


Fig.7 Flood from october 4-6,1987

- Soil water storage = 40 mm.
- Base-flow = 1.15 l/s, reflecting a 14 mm groundwater storage.

According to previously assumed calculations, with a total water storage of (40 + 14 =) 54 mm, a (270 -54 =) 216 mm precipitation is needed to generate a flood.

According to the rainfall measurements, this value was reached the 5th at 3.00 P.m., and the rise of the flood began at 8.00 p.m., after 241 mm rain.

## 5.6 October 10-12, 1987 (Fig. 8)

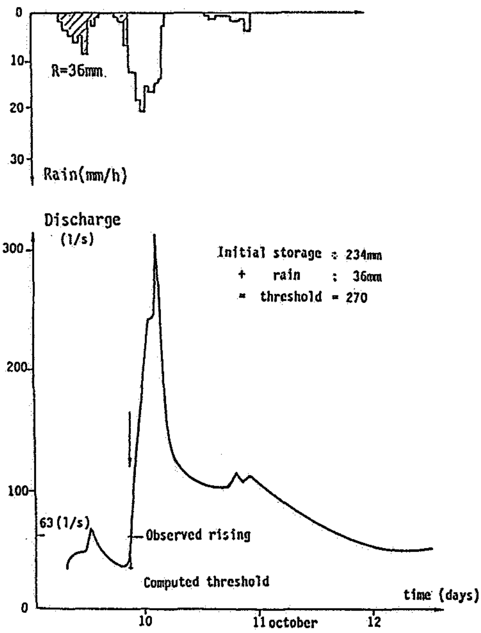


Fig.8 Flood from october 10-12,1987

The soil water storage is maximum (= 100 mm), and the groundwater storage high (=134 mm). Then, the threshold is reached after only 36 mm precipitation the 10th at 9.00 a.m. The peak accuratly began at 9.30 a.m., after 44 mm rain.

## 6 Discussion

Table 1 shows computed and monitored values for the rain preceeding the beginning of the flood, and computed and monitored values for the total water storage before the beginning of the flood.

Table 1. Comparison between computed and observed values for the rain and for the water storage before the beginning of the flood

| Date | Amount of rain needed to provoke the rise of the peak | | Total water storage needed to provoke the rise of the peack | |
|---|---|---|---|---|
| | Computed | Monitored | Computed | Experimental |
| 07.11.82 | 129 | 170 | 270 | 301 |
| 01.12.84 | 107 | 133 | 270 | 296 |
| 13.10.86 | 183 | 178 | 270 | not reached |
| 13.11.86 | 154 | 172 | 270 | 292 |
| 04.10.87 | 216 | 241 | 270 | 305 |
| 10.10.87 | 36 | 44 | 270 | 278 |

(the "computed rain" is the amount of rain needed to reach the 270 mm value (threshold for the beginning of the flood rise, obtained by calculation) ; the "experimental rain" is the amount of rain actually received by the watershed between the beginning of the rainfall event and the time when the discharge reaches 63 l/s).

The minimum amount of rain needed for a flood varied from 44 to 241 mm. But, the value for the total water storage needed for the same floods varied between only 278 and 305 mm. The results lead to two essential issues :

* the first one concerns flood forecasting : for any given rainfall, it would be easy to foresee, with an accuracy of about 20 mm (actually between 10 and 50) the amount of rain necessary for the flood occurrence, if the total amount of water storage in the basin is taken into account. Otherwise, the sole amount of rain is not relevant since it may vary in a rather large range : (44 to 241 mm) during the time of the study.

* the second remark applies to hydrological processes : an opposition appeared between, on one hand, very high soil infiltration capacity and the low runoff ratio observed during rainfall simulation, and on the other hand, the fact that large floods do exist and can be explained only by rapid surface runoff processes. But, the demonstration of a threshold from which the flow rises suddenly gives evidence that storm runoff is produced by the "overflowing" of temporary watertables, under particular water content conditions. These watertables reach the soil surface on wide parts of the basin, according to the "contributing areas" concept.

## 7 Conclusion

The aim of this study was to give evidence of a threshold for the total water storage within the watershed, from which high volumes of storm runoff occur. This threshold, caculated to be around 270 mm, represents an upper limit value for the water storage capacity of the catchment. The amount of rain needed to reach this value depends on the total water storage (sum of ground and soil water storage previous to the rain The field demonstration for the reality of such a threshold shows that storm runoff is produced in conformity which the "contributing areas" concept. Under such conditions, catchment geomorphology and soil deep conditions seem to be more significant factors than vegetation cover.

These observations have been collected only during autumn, when there is no frozen soils nor snow ; they might not be as relevant for the other seasons. In winter or spring, the role of the vegetation cover might interfere and lead to very different results.

## Acknowledgements

This work was carried out in cooperation with the "Programme Inter-équipe" of the "Pierre Birot" Laboratory of Meudon, France (A. GODARD, director), and of the "Bassin-versants du Mont-Lozère" programme (F. LELONG). J.-F. DIDON-LESCOT provided rainfall and runoff data. C. KUZUCUOGLU contributed to the English translation. I wish to thank them for their assistance.

The financial support was granted with the help of the EEC (Recherche et Developpement dans le domaine de l'Environnement).

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# USE OF EXPERIMENTAL BASINS DATA FOR THE EVALUATION OF SOIL-PHYSICAL PARAMETERS FOR UNGAUGED AREAS OF THE FOREST ZONE IN THE U.S.S.R. (EUROPEAN PART)

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Abstract

Six main categories of soils have been defined on the territory of the forest zone of the European part of the U.S.S.R. as a result of the detailed lithological description of the soil with the following generalization over the degree quadrants of the 1 : 1 500 000 scale map. Soil-physical characteristics have been obtained for 186 degree quadrants using the long-term field data of the GGI Valdai Branch, the Vyatsk expedition and the poor observation data from an agrometeorological network. The Valdai Branch data are noted to be representative for the prevailing part of the territory under study.

Hydrological processes in any physiographic zone significantly depend on general humidification of a territory and accumulating capacity of the soil as a medium, transforming precipitation into river runoff. Accumulating capacity and water regime of soils depend on soil-physical parameters and, in the first turn, on porosity, density and water retaining capacity.

Disturbance of natural soil structure due to man's activity (forest cutting, reclamation, etc.) causes changes of soil-physical properties and of the water regime of soils which results in changes of the runoff.

In general, there is a lack of soil-physical parameter data in hydrometeorological observations. So, when carrying out vast areal generalizations concerning runoff formation and water balance investigations, natural research data obtained from experimental basins may be used for ungauged territories. Such generalization has been performed for the forest zone of the U.S.S.R. European part, which is characterized by the great variety of soil lithology. The territory under study covers 17 regions and 5 autonomic republics (about 12 x 10,5 $km^2$). It occupies the large part of the Russian plain and the Upper Volga landscape area. Its north-western and central parts are related to the mean- and south-taiga subzone, its south-eastern part to the forest-steppe zone.

The north-western and central parts of the territory were subjected to glaciation which resulted in an extreme variety of soils in terms of texture, as well as in lack of soil structureness. The south-eastern part of the forest zone is characterized by the relatively homogeneous texture and by a rather high degree of its structure.

Soils have been mainly formed by quaternary and present deposits represented by moraine and topsoil loams, sandy loams and sands, carbonate and loessial loams, glacial lake sands and sandy loams, underlied by loams. Sands are mainly placed nearby sea beaches, river and lake valleys. Loamy and sandy-loamy deposits are mostly spread. The soil cover is characterized by podzol, sod-podzol and grey forest types of soil.

The territory covers 186 degree quadrants of a soil map with the scale 1 : 1 500 000. When analyzing, each degree quadrant was subdivided into 100 quadrants and description of ground was made, taking into account all information available. Then the generalization was performed within each degree quadrant which resulted in marking out 6 soil types (Table 1).

Using the experimental data of the Valdai Branch and the IHP experimental basins network as well as the GGI expedition episodic data, the values of the main soil-physical parameters such as volume weight, full, capillary and field capacities, and wilting point were determined. Herein, the poor information of the agrometeorological network was used as comparative. Preliminary comparison showed small differences of these parameter values (within the limits of each soil type) for the regions of the north-western and central parts of the forest zone. In general they are close to the values obtained at the experimental basins of the Valdai Branch (Table 1). As to the south-eastern part of the zone there have been noted some peculiarities due to more homogeneous soil textures (Table 2).

Table 1. Soil-physical parameters* for different soil types of the north-western and central parts of the forest zone

| Type of soil | VW | | FC | CC | FiC | WP | VW | | FC | CC | FiC | WP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40-50 cm | 90-100 cm | 0-100 cm | | | | 40-50 cm | 90-100 cm | 0-100 cm | | | |
| | Field | | | | | | Forest | | | | | |
| Coarse and medium grained sands | 1.56 | 1.61 | 406 | 327 | 205 | 56 | 1.30 | 1.63 | 452 | 320 | 197 | 73 |
| Fine sands, light sandy loams | 1.59 | 1.63 | 400 | 336 | 214 | 60 | 1.55 | 1.63 | 414 | 313 | 220 | 70 |
| Medium and hard sandy loams | 1.60 | 1.68 | 386 | 346 | 241 | 94 | 1.52 | 1.67 | 435 | 346 | 251 | 105 |
| Light and medium loams | 1.63 | 1.75 | 365 | 339 | 282 | 106 | 1.64 | 1.74 | 392 | 331 | 277 | 109 |
| Hard loams with sands and gravel ingrained | 1.66 | 1.76 | 360 | 334 | 290 | 120 | 1.67 | 1.76 | 381 | 323 | 294 | 117 |
| Hard dense loams | 1.80 | 1.88 | 372 | 353 | 305 | 147 | 1.79 | 1.85 | 410 | 333 | 291 | 120 |

* VW - volume weight (g/cm$^3$) FC - full capacity (mm) CC - capillary capacity (mm)
FiC - field capacity (mm) WP - wilting point (mm)

Table 2. Soil-physical parameters* for different soil types of the south-eastern part of the forest zone

| Type of soil | VW | | FC | FiC | WP |
|---|---|---|---|---|---|
| | 40-50 cm | 90-100 cm | 0-100 cm | | |
| Coarse and medium grained sands | 1.46 | 1.55 | 460 | 1000 | 65 |
| Fine sands, light sandy loams | 1.46 | 1.55 | 460 | 150 | 70 |
| Medium and hard sandy loams | 1.48 | 1.55 | 460 | 220 | 110 |
| Light and medium loams | 1.48 | 1.54 | 460 | 300 | 120 |
| Hard loams with sands and gravel ingrained | 1.48 | 1.54 | 460 | 300 | 130 |
| Hard dense loams | 1.48 | 1.54 | 460 | 300 | 150 |

* VW - volume weight (g/cm$^3$) FC - full capacity (mm)
FiC - field capacity (mm) WP - wilting point (mm)

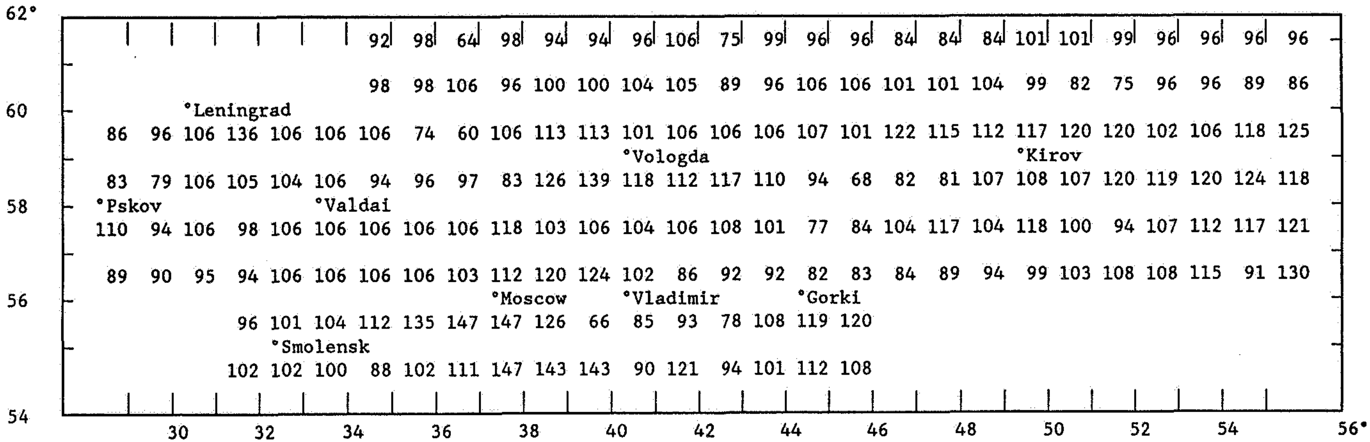


Figure 1. Wilting point distribution over the forest zone territory (0 - 100 cm layer)

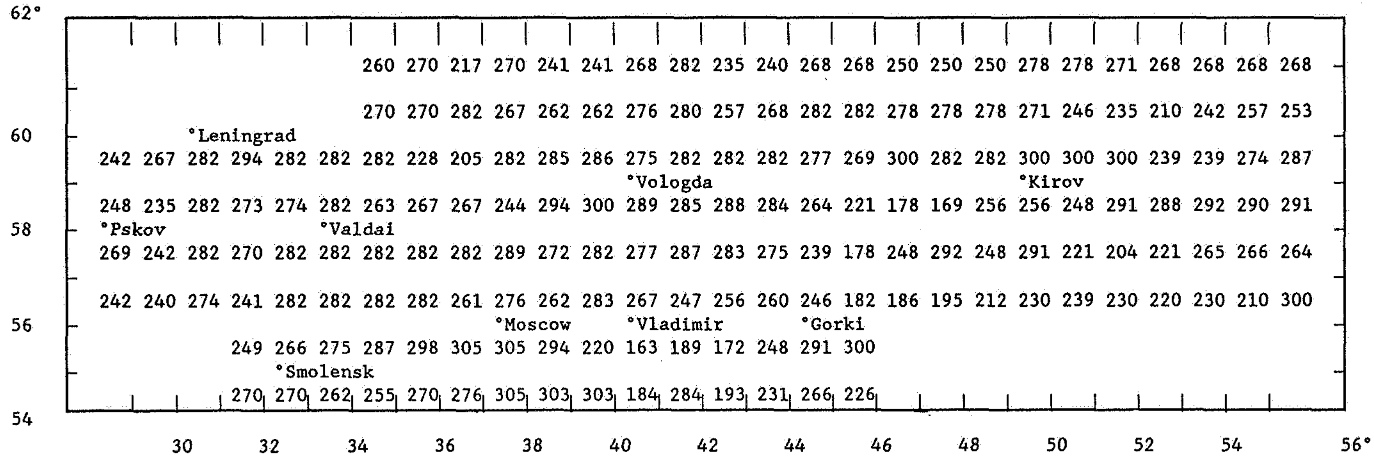


Figure 2. Field capacity distribution over the forest zone territory (0 - 100 cm layer)

Tables 1 and 2 show volume weight for two distinctive layers: 40-50 cm as being a transitional one from humus horizon to parent rock; and 90-100 cm where any incidental factors (e.g. plant root system, organics, etc.) practically have no influence on the special variability of the volume weight and other parameters. Data on full, capillary and field capacities and wilting point refer to the 0-100 cm layer. The characteristics given in Tables 1 and 2 were used when calculating their averages for the degree quadrants of the forest zone map. In case of the great lithological variety within a quadrant the characteristic value was determined as a weighted average.

Taking into account, that in some regions of the forest zone the greater part of the territory is covered by fields, the ratio of soil-physical properties of the field and forest soils is of interest. The main distinctions are known to be dependant on differences in porosity, which is greater in the forest compared with the field due to the loosing effect of the forest vegetation root system (Kapotov, 1980). This fact explains the smaller volume weight and the larger full capacity values for forest soils (Table 1). Relative discrepancies for soil-physical characteristics are 10-15%. The least difference (2-4%) is for field capacity values.

The results of the study are presented in the form of map-schemes given as an example in Figures 1 and 2, and also in summary tables (Kapotova, 1988), containing the full data for 186 degree quadrants. The results show that the distribution of soil-physical parameters is in accordance with the soil type variation. For example, the volume weight in the north-western and central parts changes from 1.56 to 1.80 in the 40-50 cm layer and from 1.61 to 1.88 in the 90-100 cm layer. However, it is possible to distinct rather vast regions in which the volume weight fluctuations are negligible (the Valdai Hills, Leningrad, Smolensk and Moscow regions). More uniform distribution of volume weight is noted in the south-eastern part of the forest zone. The volume weight of structure loams in these regions is 0.2-0.3 g/cm$^3$ less compared with that in the north-western and central parts.

The character of the water content changes is also subjected to the soil distribution regularity. The wilting point and the field capacity have the greatest changes over the area (2-2.5 times and 1.5-2.0 times, respectively) while the full and capillary capacity fluctuations do not exceed 10%.

The present investigation is mainly based on experimental basins data and resulted in soil-physical parameters for vast poor gauged territory. A conclusion can be drawn about the representativity of the Valdai Branch experimental data to the larger area of the forest zone of the U.S.S.R. (European part).

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# DESIGN OF A SOIL MOISTURE MEASURING NETWORK IN A SMALL RURAL CATCHMENT

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## Abstract

The installation and the operation of a soil moisture measuring network in an experimental catchment are described. The data are collected once a week by means of a TDR-instrument. The network consists of about 60 locations in an area of 6 square kilometers. There are 5 different sample depths at each location. The analysis of the data taken during a 6 months period includes the mean behavior in time, two kinds of point-correlations, the time-variance of the measurement points and examples for variograms. Conclusions for possible modifications of the network and of its operation are discussed.

## 1 Introduction

The present paper describes the first step of an investigation with respect to the spatial variability of infiltration parameters in a small rural catchment. The research is part of a comprehensive project located at Karlsruhe University whose objective is to balance the water and material transport in a rural catchment. The general ideas of this basin study for pollutant transport and the underlying modelling concept are given in Buck and Plate (1990) and Bronstert (1990), respectively. This paper presents the first results from a soil moisture measuring network in the investigated research basin called 'Weiherbach Catchment'.

## 2 Collecting soil moisture data

Time Domain Reflectometry (TDR) is used for the single moisture readings at the network points. The fundamental principles and the application of TDR for measuring soil water content are described in Topp et al. (1983 and 1985). In this study the TDR-instrument 'IRAMS' supplied by 'Soilmoisture Equipment Corp., Santa Barbara, U.S.A.' is used. Figure 1 shows the installation principle of TDR-wave-guides with the penetration depths 15, 30, 45, 60 and 75 cm and a schematic step-like moisture content profile which is the desired result after evaluating the differences between TDR-readings of two pairs of wave-guides with different depths.

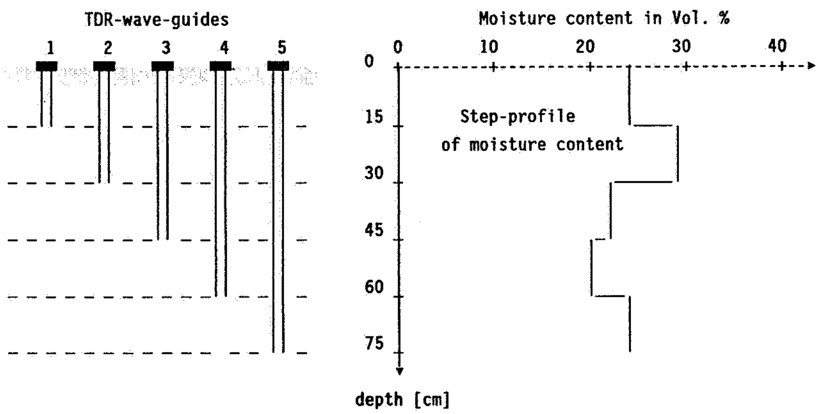


Figure 1. Installation principle of TDR-wave-guides and desired profile

The measurement of soil water content using a TDR-instrument provides a quick and nearly non-destructive means for collecting moisture data. Theoretically no calibration is needed, but problems can arise because of discontinuous distributed moisture contents along the wave-guides. Nevertheless, the TDR-instrument 'IRAMS' made it possible to carry out up to 300 moisture readings during one working day. The 300 readings, which are taken once a week, result from the 5 wave-guide-depths shown in Figure 1 at about 60 locations distributed in the 'Weiherbach Catchment'. A topographic map and the preliminary selected measurement points are shown in Figure 2.

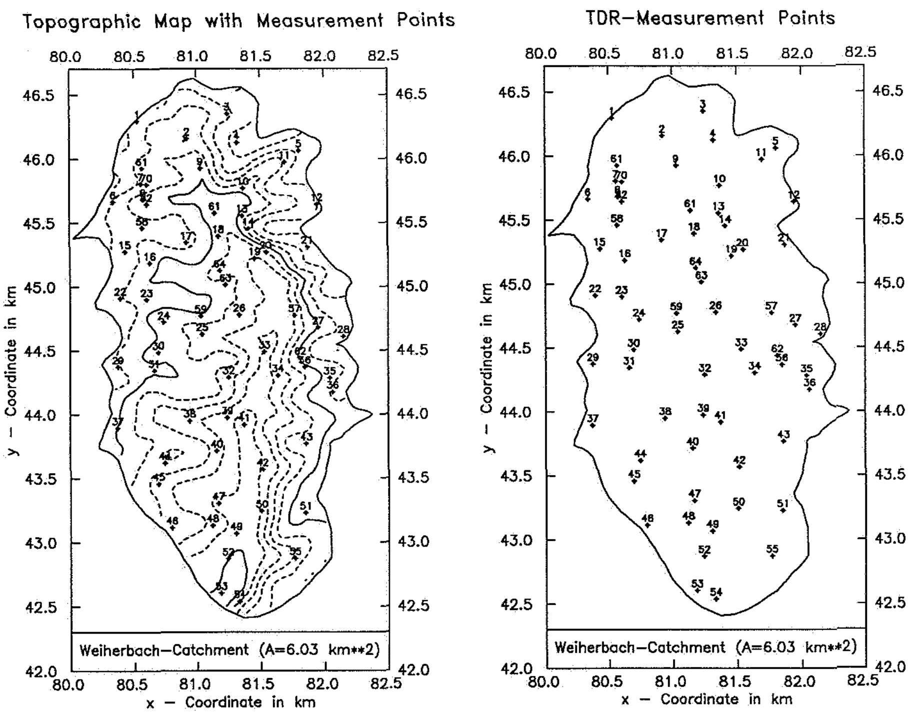


Figure 2. Topographic map and TDR-measurement points

# 3 Data Analysis

## 3.1 Mean Behavior of all Points

The mean moisture contents of all network points calculated for the 5 TDR-depths at 28 dates are shown in Figure 3. The number of sample points for each TDR-depth is about 60. The standard errors of the estimated mean values are always about 1 percent moisture content.
Carrying out the moisture readings at all locations shown in Figure 2 takes about 8 hours. In special hydrological situations, e.g. after heavy precipitation, it could be useful to do a quicker reading with a subset of the whole network which should deliver at least an estimation of the mean behavior of the network . Figure 4 shows the so called

'representative points for the mean'. These points were selected because their single values over all TDR-depths are often very close to the mean values of the corresponding depths.

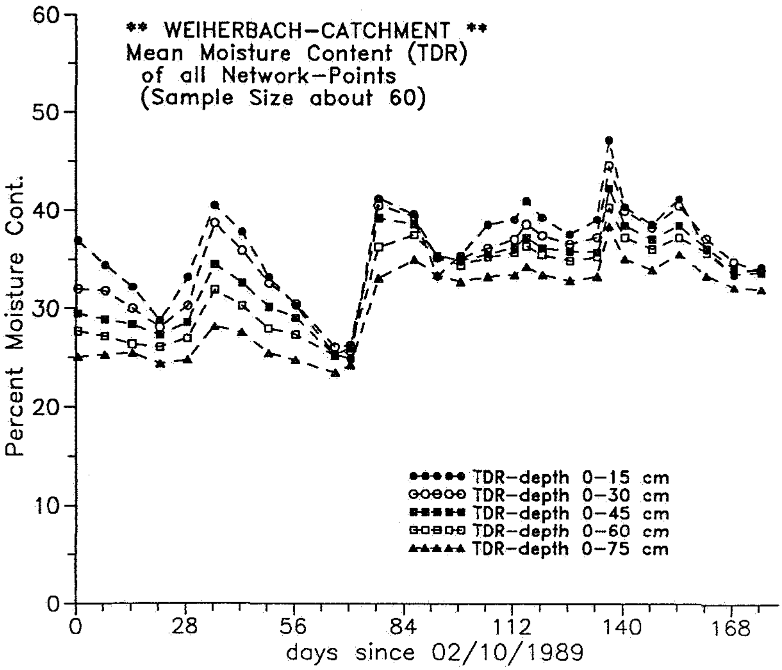


Figure 3. Mean moisture contents calculated from all network points

## 3.2 Single point to mean correlations

It is likely that some of the single measurement points have a moisture regime similar to the mean behavior of all network points but on another level. To examine this, the correlation coefficients between all single point time series and the mean time series for the 5 TDR-depths were calculated. The areal distributions of the correlation coefficients are shown in Figure 5.

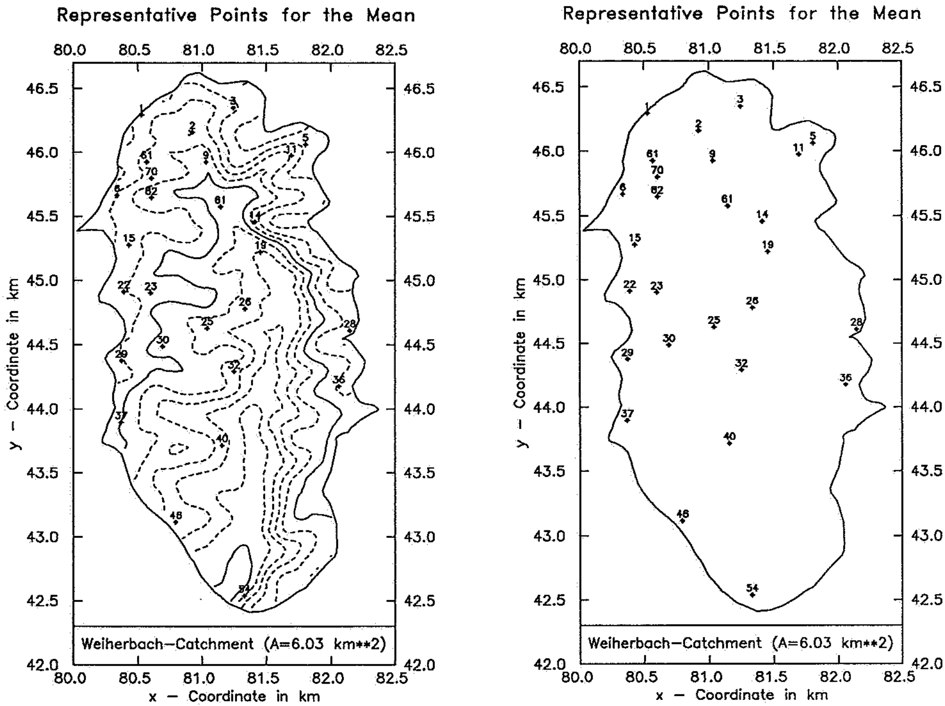


Figure 4. Representative points for the mean behavior

## 3.3 Point to point correlations

It is again very likely that some of the single measurement points show a time behavior similar to other single measurement points. To examine this, the correlation coefficients between single point time series were calculated. Figure 6 shows a set of sample locations whose time series show a high correlation ($r \geq 0.9$) to those of other points.

## 3.4 Variance in time

One reason for weakly correlated time series at some single points may be their time-invariant behavior. The variances of the single point time series were calculated and the results are shown in Figure 7.

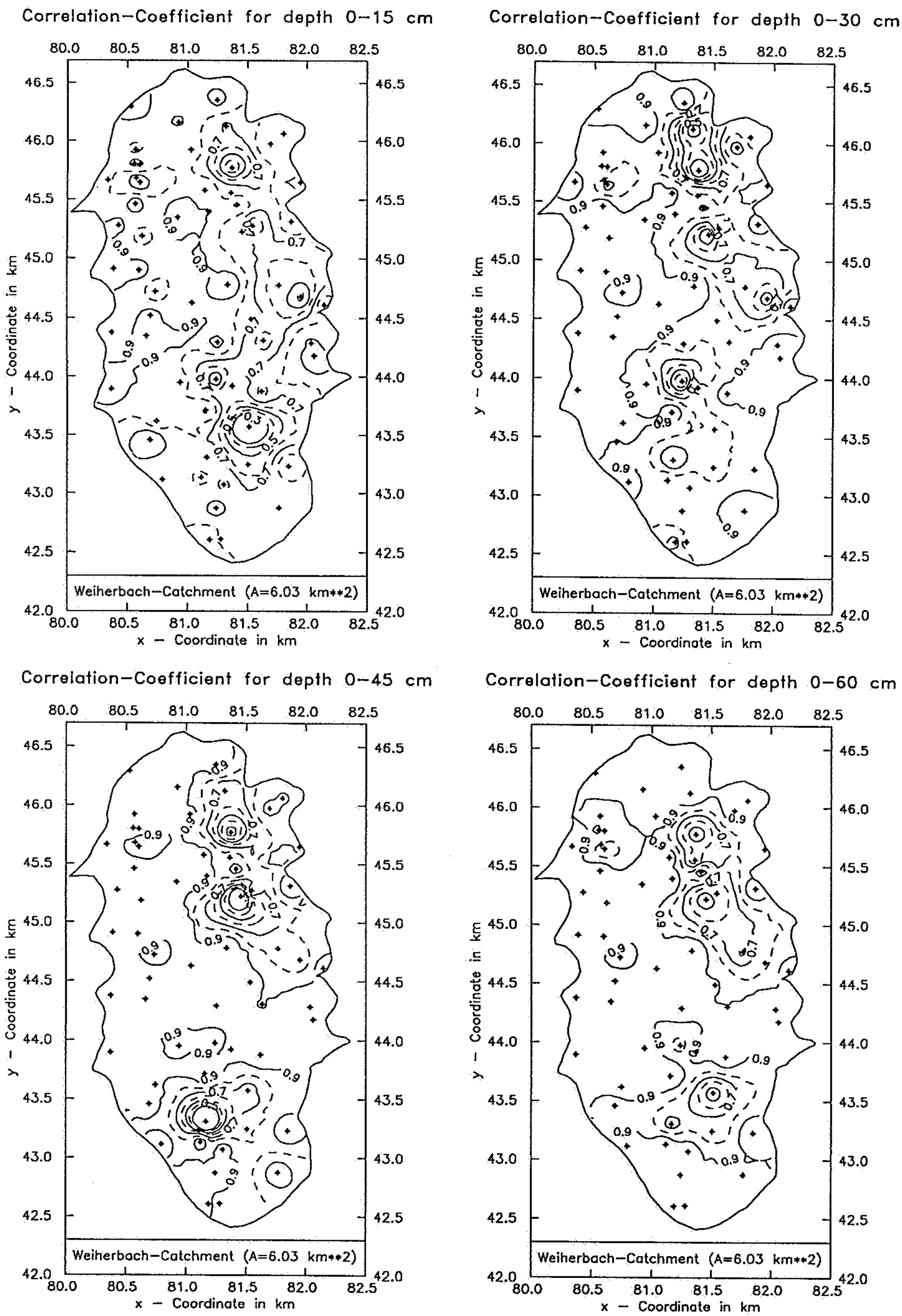


Figure 5. Single point - mean behavior correlation coefficients

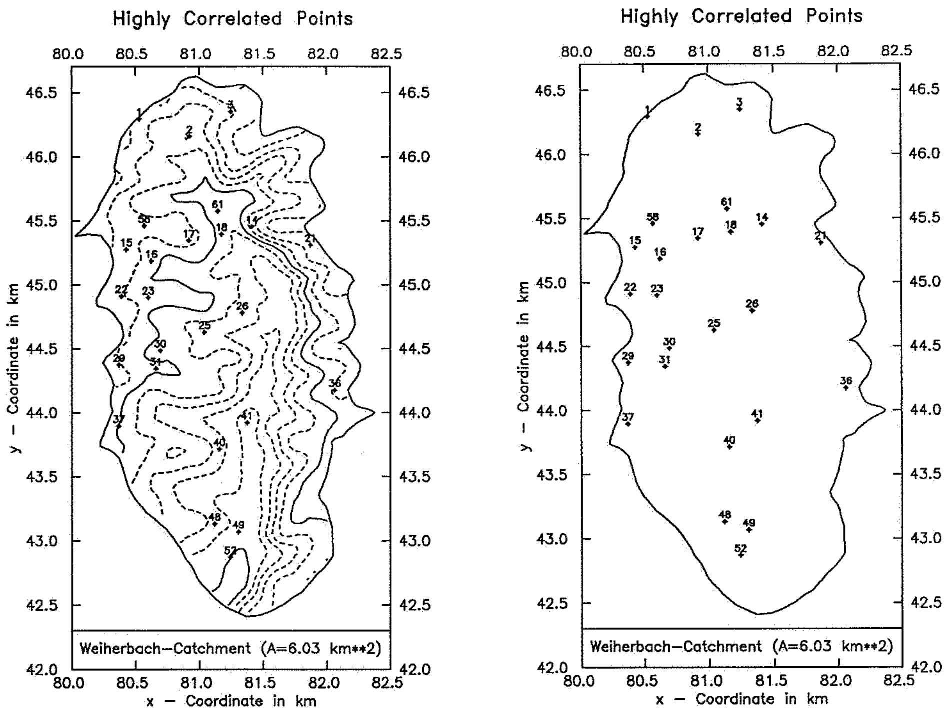


Figure 6. Points with mutually high correlation $(r \geq 0.9)$

## 3.6 Variograms

The variogram of a regionalized variable is defined as the semi-variance (one half of the mean squared difference) of paired measurement values at different locations as a function of the vector separating them. It is often assumed that the semi-variance depends only on the distance and the direction between the sample points and not on the location itself. Variograms provide a means of quantifying the commonly observed fact that samples close together will tend to have more similar values than samples far apart. Figure 8 shows the variograms of 4 TDR-depths for an intermediate moisture situation (last record in Figure 3) in the Weiherbach Catchment. The variograms were calculated by means of the geostatistical software GEO-EAS (Englund and Sparks, 1988).

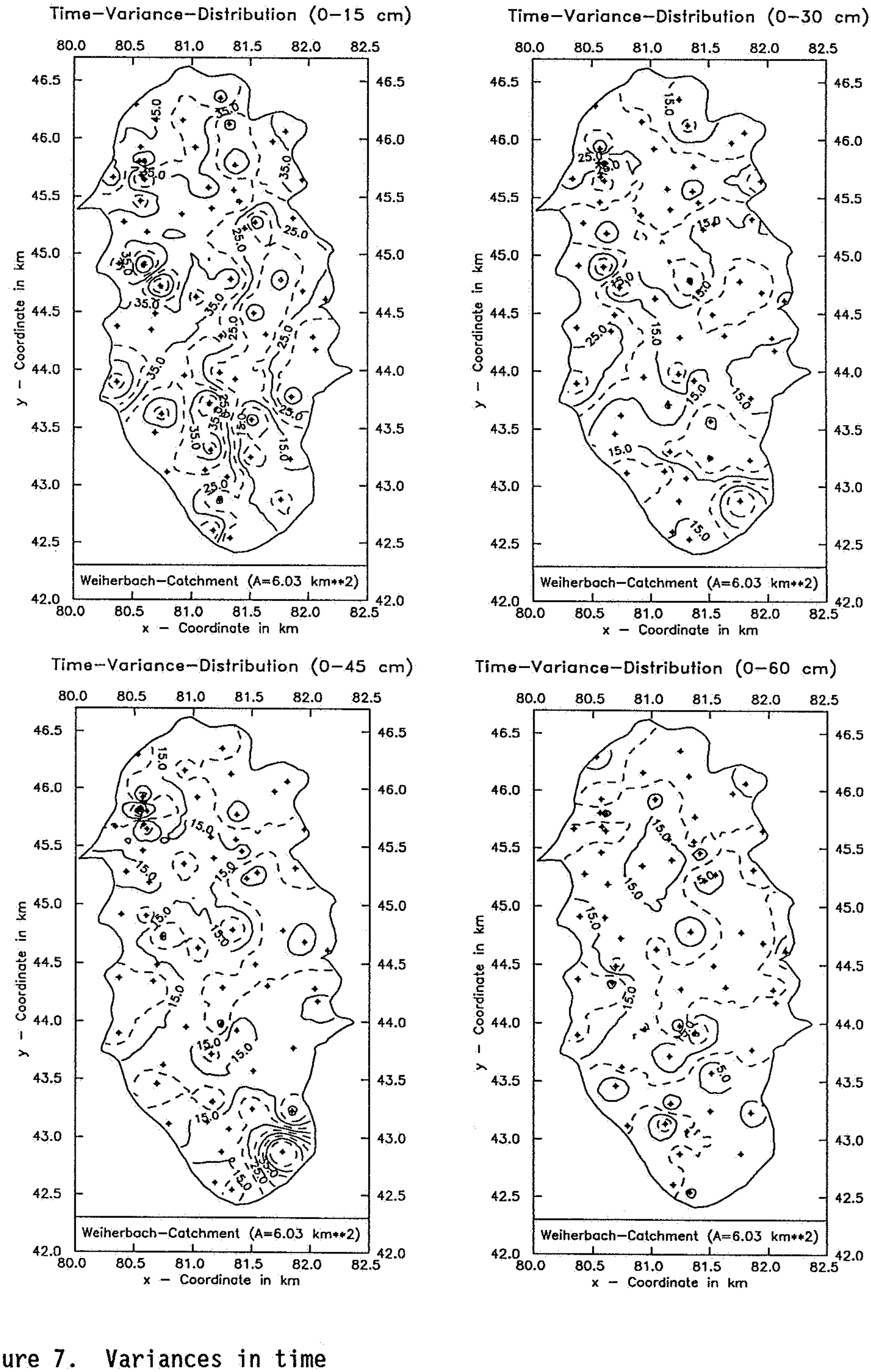


Figure 7. Variances in time

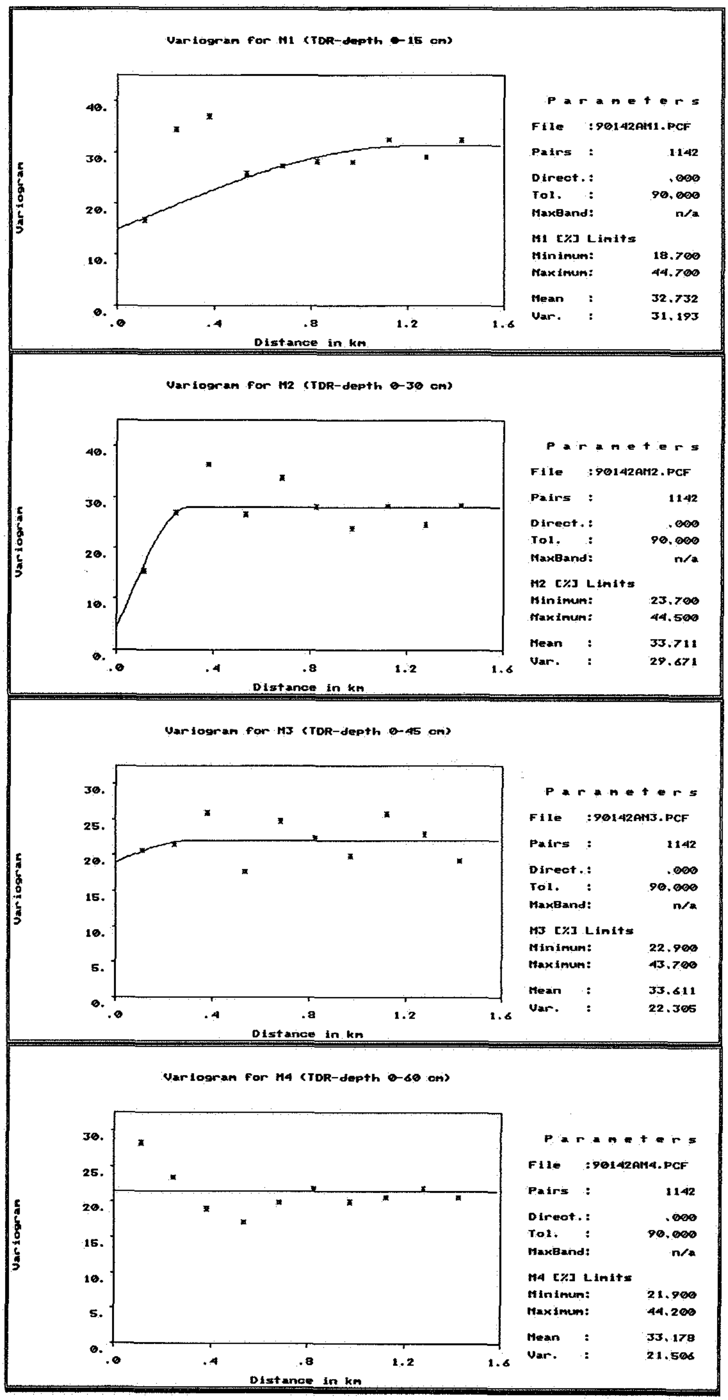


Figure 8. Variograms for an intermediate moisture situation

## 4 Conclusions

The variograms for different TDR-depths show a rather non-uniform relationship between the semi-variance and the distance. The nugget-values are high, the ranges difficult to define and sometimes the semi-variance has its highest value at the shortest increment. Because of the expected high interpolation errors, e.g. by means of kriging, it is desirable to get a higher network density by installing much more sample locations. But only about 60 locations can be sampled at one day.
The correlation analysis shows that many sample points are well correlated to the mean values or to other sample locations. These relationships should be used to develop an strategy for carrying out moisture readings once a week at about 60 sample locations which should consist of weekly changing subsets of a network, e.g. of 90-100 points.

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## MAN-MADE EFFECTS

# THE RESEARCH BASIN AND STATIONARITY

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## Abstract

Studies of the runoff of two catchments in Britain show evidence of a change in flow response over time although both are rural in character and without noticeable land use changes. The mechanisms responsible have been the subject of a number of small scale process studies within the catchments.
The fact that changes in flow response have occurred even in these apparently stable catchments suggests that the assumption of stationarity which is implicit in most hydrological and flood frequency and design studies should be questioned.

## 1 Introduction

Research basins have traditionally been divided into 'representative' catchments (which are supposedly typical of a particular type of countryside) and 'experimental' basins which are undergoing some change (usually in land use). Representative basins may also be used as 'controls' for comparisons with experimental basin outputs, or to show the impact on flows of changes in climate. Data from catchments are also needed for operational and design purposes by engineers, and by making the assumption of stationarity (i.e. past records are the best guide to future conditions) implicitly use the catchments as 'representative' basins. It is evident, however, that with increasing human pressures on the land that even representative basins may be subject to change, which may be subtle in nature, and so become experimental basins.

There has been a multitude of catchment studies of the relation between changes in land use and streamflow, and they have used a large number of differing techniques of data analysis. The simplest methods examine changes in the flow records alone and are of limited value due to the natural variability of climate, especially flood producing events. Even where the flood records are related to records of daily precipitation the results may be inconclusive due to the difficulty of apportioning any observed change in flows between changed rainfall inputs or catchment storage and routing characteristics. Broadly coincident changes in the frequency of flooding over large areas of W Europe were, for example, demonstrated by Arnell (1989) using data collated for the FREND project, and are the result of large scale changes in weather systems.

To determine whether the runoff response of a catchment has altered it is necessary to make allowance for the storm rainfall characteristics. Two widely used field-based techniques are the 'paired catchment' and the 'experimental catchment' approaches. In the former, differences in storm characteristics and antecedent conditions are accounted for by comparison with flows from a 'control' catchment. This method enables direct comparisons to be made, but suffers from the disadvantage that no two catchments are identical in all other respects (soils, slopes etc). The experimental catchment approach, whereby the response of a catchment is studied under changing conditions requires a long period of record, but is the more appropriate technique for large river catchments, since a partial change in land use over a period of time is generally what really happens in practice.

In parallel with such field-based approaches, and in many ways complimentary to them, mathematical modelling techniques may be used to characterise the rainfall-runoff relation of a given catchment in one period and then be used to detect changes from this behaviour by comparison with observations in other periods. This methodology was adopted in this paper.

## 2 Study catchments

Two catchments were selected for detailed study: The Ray in S England and the Catchwater in E England. Both catchments have hydrometric data, including rainfall and flows, dating back to the mid-1960's. They are predominantly rural, with no significant urban development, and their flows have been classified as being essentially 'natural' (IH, 1988). In common with many part of W Europe they are in areas which have experienced a rapid intensification in agricultural production. Over the last 20 years the land use in the Ray catchment has remained largely unchanged (predominantly pasture) whilst the Catchwater catchment has experienced a small increase (about 10%) in the area of arable at the expense of grassland. Summary characteristics of the catchments are given in Table 1.

Table 1. Summary of the characteristics of the study catchments

| Name | Area ($km^2$) | Mainstream slope (m/km) | Soil type | Principal land use |
|---|---|---|---|---|
| Ray | 18.6 | 4.82 | Clay | Grass |
| Catchwater | 16.1 | 1.29 | Loam | Arable |

Land use in the Ray comprises permanent grass (60%) with some areas of arable (20%), whilst the Catchwater has predominantly arable farming (80%) and only a small area of permanent grass (20%). The soils of the Ray catchment are formed on virtually impervious clays with poor natural drainage, and are waterlogged for a significant part of the year whilst the Catchwater has better draining loam soils.

## 3 Studies of runoff

Data from both basins have previously been used in a number of studies, and are considered to be relatively free from serious errors. The main elements of the water balance were discussed by Edwards and Rodda (1970) for the Ray and by Tang and Ward (1982) for the catchwater and both are considered to be watertight. Daily hydrometric data were satisfactorily modelled by Eeles (1978) for the Ray, and by Ward (1984; 1985) for the Catchwater. The short term response of the Ray to storm events was examined by Beven (1980), using hourly data, who found that the peak discharge may be increasing slightly over time while the time to peak may be decreasing. Neither variable was, however, statistically significantly correlated with time, and he pointed to the problem of distinguishing changes 'in the face of year to year variability of rainfall and other factors affecting antecedent conditions'.

In the light of these inconclusive results a detailed examination of storm rainfall runoff behaviour was undertaken for both catchments, using hourly rainfall and flow data. As a first stage the pattern of occurrence of peak flows over time was examined (using a Poisson model to describe the frequency of peaks above given thresholds). There was no statistically significant trend for the Ray, but a significant increase in the number of peaks on the Catchwater (at 5% level). To investigate the response of both catchments in more detail the hourly rainfall and flows associated with the highest peak flows in the period of record were selected for detailed study, using the unit hydrograph approach (Fig 1). Events with multiple peaks or a snowmelt contribution were excluded from the study. Both catchments showed evidence of a change in runoff response over time. The Ray's unit hydrographs became more peaky (at 0.5% significance level, n=26, Mann Whitney test) but response times were no different, whilst those for the Catchwater had higher peaks and shorter response times (both significant at the 5% level, n=10).

These results indicate that there was an increase in peak storm response in both catchments, although it is difficult to quantify the effect on river hydrographs without knowing if storm runoff quantities were changing too. No significant differences were detected, but this may simply reflect the large variability from one storm to another due to antecedent conditions, or to difficulties in applying an arbitrary baseflow separation in the light of changing hydrograph shapes.

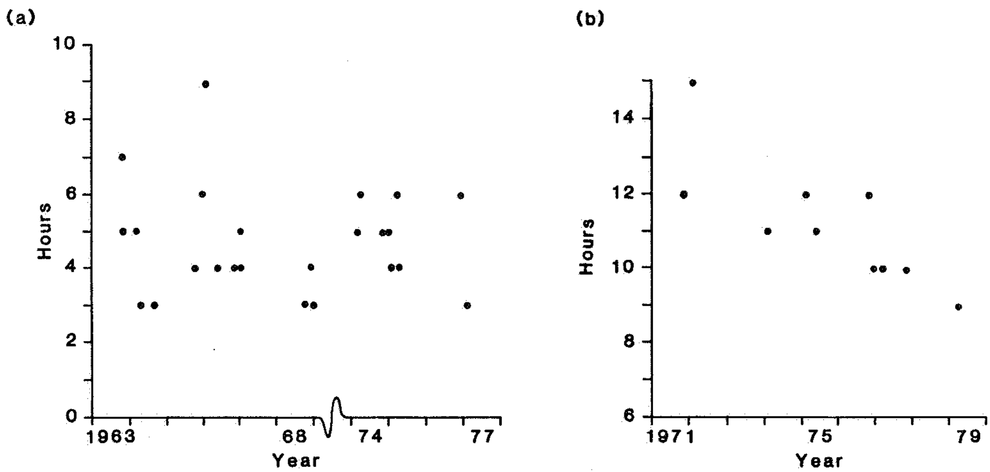


Figure 1. Changes in storm runoff timing for the a) Ray and b) Catchwater catchments (shown by the time to peak of the one hour unit hydrographs)

To try to overcome these problems a lumped conceptual model (Eeles et al, 1990) was fitted to the early part of the record for each catchment, and then used with unchanged parameters to simulate the flows in the later periods. The model gave a very good fit to the total flows over the whole period indicating little or no change in the water balance of either basin. When the comparison is restricted just to the higher flows (>0.4 mm/hr for the Ray and >0.2 mm/hr for the less responsive Catchwater) it is evident that there was a tendency to an increase in flow magnitudes over time on each catchment (Fig. 2). This increase was particularly marked for the Catchwater.

## 4 Causes of observed changes

Given that both catchments are free from urban influences and the land is mainly used for farming, it is apparent that with increasingly intensive agricultural production even representative basins may be subject to change, which may be subtle in nature, and so in fact become experimental basins. Neither catchment has undergone significant changes

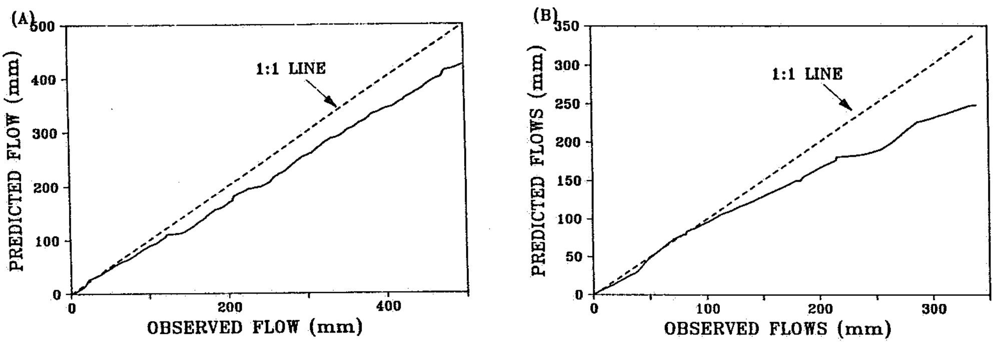


Figure 2. Changes in peak flows over time, using predicted and observed data for the a) Ray and b) Catchwater catchments

in land use; over the period of flow records the Ray has remained under similar areas of grass and arable whilst the Catchwater has experienced a small increase (about 10%) in the area of arable at the expense of grassland. Each catchment has, however, received significant amounts of artificial drainage, both to increase productivity and to improve winter access onto the land with heavy machinery. Over the period from 1960-80 about 40% of the Ray and 25% of the Catchwater were artificially drained using subsurface pipes.

The effects of such drainage on downstream flooding has long been a source of controversy. Both catchments have had small scale process studies of field drainage. These have indicated that drainage of the clay soil in the Ray results in smaller peak winter flows than from the undrained land (Robinson and Beven, 1983), whilst drainage increased peak flows in a field experiment in the Catchwater (Robinson, Ward and Ryder, 1985). This difference conforms to the general pattern of drainage effects proposed by Robinson (1989), namely that it reduces peak flows from clayland soils but increases maximum discharges from more permeable soils.

This study has shown that in the case of the Ray catchment the impact of drainage may be different at the catchment and the field scales. The apparent anomaly is due to the intervening storage and lag effects of the stream network and any 'improvement' works to these channels. Information from the local water undertakings and from farmers confirmed that new field ditches had been cut and the main stream channels had been enlarged and deepened in both catchments. Whilst for the Catchwater, peak flows were increased both by the field scale drainage work and by the channel improvements, in the Ray catchment the observed increase due to the channel works is partly counterbalanced by the reduced field scale peaks. The effect of scale is of fundamental importance in hydrology, and different processes may be important as different sizes of catchment are considered. Thus, if these results are extrapolated to larger catchments, the importance of channel routing on the stream hydrograph is likely to increase.

## 5 Conclusions

Data from two small lowland catchments in Britain have been used for a variety of investigations, including water balance studies and the individual components of the hydrological cycle. Both catchments are rural and have undergone little change in the broad types of land use. Recently, analyses of the long time series of records now available have, however, provided evidence of non-stationarity in the storm rainfall-runoff response of both basins. This change has been investigated and quantified by calibrating a lumped conceptual model to the early part of the hourly historic record from each catchment and then running the model with unchanged parameters on the later data. This enabled the change in flow regimes over time to be quantified and, most importantly, for them to be separated from the results of variability over time in the climatic inputs. The overall water balance of each catchment remained relatively unchanged but there was a shift to a more responsive storm runoff pattern. The fact that these changes in flow response had occurred on both these rural catchments indicates that the assumption of stationarity, fundamental to so many hydrological applications, may need to be questioned, even for such apparently stable catchments.

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# DETERMINISTIC VERSUS CONCEPTUAL MODELS TO EVALUATE INFLUENCE OF DRAINAGE ON WATER REGIME

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## Abstract

SIDRA is a deterministic saturated groundwater model for subsurface drainage, comprising a peakflow term proportionnal to rainfall intensity ; its input parameters can be measured in situ. GR3 is a conceptual rainfall-runoff model, requiring only 3 parameters to be calibrated on observed outflow values. Using the Rosenbrock optimization technique, SIDRA and GR3 parameters were calibrated on outflow data collected in Arrou experimental drainage field. Parameters of SIDRA peakflow term could be calibrated only after a threshold-value was introduced on data used to calculate the object function. Dependency between some parameters of SIDRA is revealed by response surface map analysis. This dependency can be suppressed using a proper reparameterization : as a result, the two sets of equations governing both models happen to be formally identical, leading to practical considerations about relations between deterministic and conceptual models. After calibration, both models proved to give satisfactory predictions of drainflow rates.

## 1 Introduction

Conceptual models are based on a simple arrangement of a relatively small number of water-balance components. Groundwater models are often deterministic, physically based models : examples of models for groundwater saturated flow are the model of Kraijenhoff-Van de Leur (1958), and DRAINMOD (Skaggs, 1982). The former is based on the linearized equation of motion. Its unit hydrograph is Glover's equation (Dumm, 1954), the *initial discharge of which is infinite : realistic analysis of peakflow* is not possible with this model. The latter, based on Hooghoudt's equation for subsurface flow, does not contain any peakflow term. SIDRA is a deterministic model predicting hourly mid-point water-table heights and drainflow rates, including peakflows, in seasonally waterlogged soils (Lesaffre and Zimmer, 1988). The version used in this study assumes that drains rest on the barrier and that soil properties are power functions of elevation : it requires six input parameters, that can be derived from water-table height and drainflow rate tail recession curves. GR3 is a rainfall-runoff conceptual model with three parameters (Edijatno and Michel, 1989).

Drainflow rates are more often measured than water-table heights. Consequently, in the present study, they are used to calibrate SIDRA's parameters, so that (1) SIDRA might be applied on drained plots where only drainflow rates are measured, and (2) parameters sensitivity may be tested. Sensitivity analysis on a deterministic model, using soil hydraulic properties as input parameters, aims at developing a strategy for measurement of the most sensitive parameters of the model.

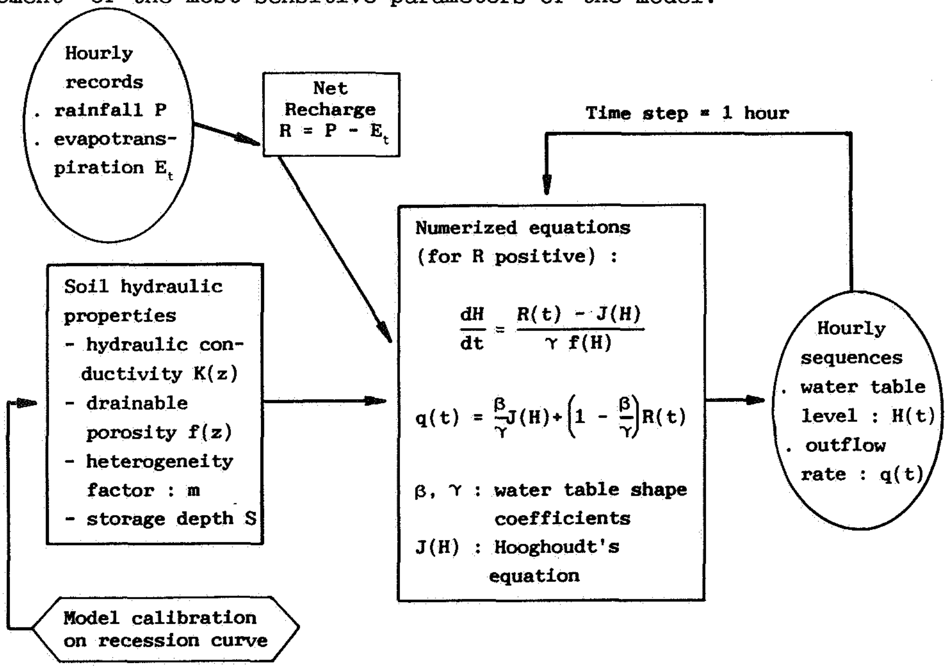


Figure 1. Simplified flow chart of SIDRA model

Interest for comparing SIDRA and GR3 is twofold (Favier, 1989) : first, both models were developed from quite a different point of view, SIDRA for subsurface drained agricultural plots (Figure 1) and GR3 for predicting runoff in catchments of a few $km^2$ to thousands of $km^2$ (Figure 2) ; second, the quadratic discharge transfer function of GR3 resembles to the first part of SIDRA's transfer function.

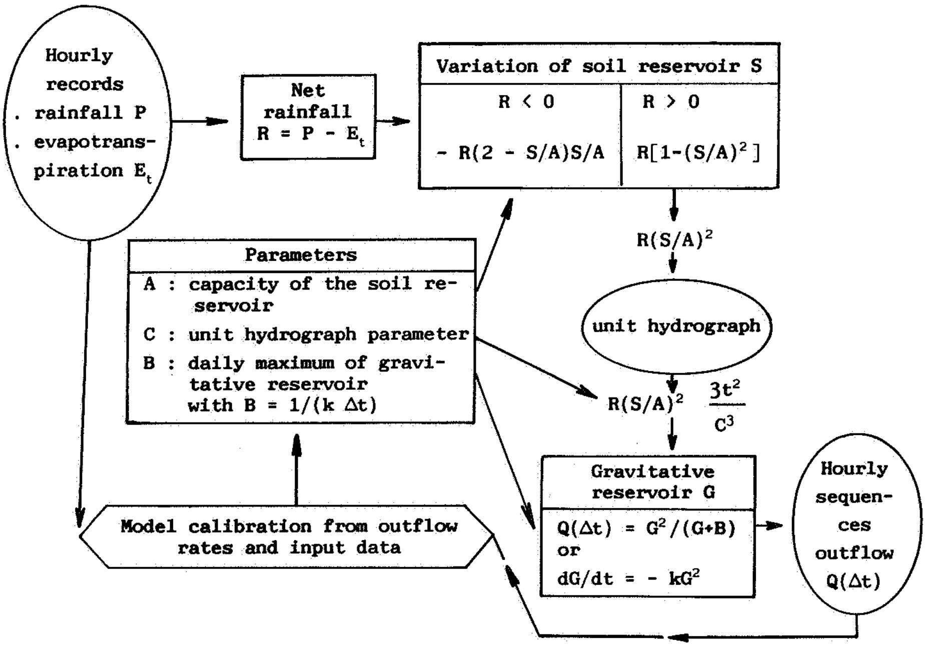


Figure 2. Simplified flow chart of GR3

## 2 Material and methods

Hourly drainflow and rainfall rates were measured on plot 1 of Arrou experimental field ; daily evapotranspiration was calculated at the nearby weather station, and transformed into hourly data using a sine function during part of the day-time. The 15-year old experimental and representative drainage basin of Arrou is located on a leached soil (albaqualf) developed on a plateau loam. Below the plough layer (0-0.25 m), the subsoil comprises an albic horizon (0.25-0.5 m) lying over an argillic horizon. The depth to the barrier is about 0.75 m. The mean ground slope is 0.5%. The field is equipped with V-notch weirs associated with an ultrasonic head-level recording gage and a tipping-bucket rainfall recorder. The nominal parameters of SIDRA had been determined by Guyon (1983) from both water-table height and drainflow rates tail recession curves analysis. Data of three intense drainage seasons, as defined by Lesaffre and Morel (1986), were used. SIDRA was calibrated with 2207 hourly data of 1980-1981 winter and validated with 3840 data of 1982-1983 winter. GR3 was calibrated with the same 1980-1981 data and validated with the 1982-1983 and 1984-1985 winter data. The classical Nash and Sutcliffe (1970) function, noted F, was used as object function for calibration. In the calibration procedure, the optimal parameter values were searched in a limited sector of the response space, and two sets of initial parameters, a lower bound and an upper bound sets, were introduced. The Rosenbrock (1960) optimization technique was used.

## 3 Calibration and validation of SIDRA

Without indroducing neither threshold nor time-lag, results (Favier 1989) show that (1) the calibrated set is not unique and is always far remote from nominal values, and (2) the F-value, always fairly high after calibration (between .84 and .86), drops near to .70 during validation (Table 1).

Table 1. Results of SIDRA calibration (without threshold nor time-lag) starting from low and high initial values

| Parameter | Lower bound initial value | Calibrated value | Upper bound initial value | Calibrated value | Nominal value |
|---|---|---|---|---|---|
| $K/L^2$ $m^{-1}$ $d^{-1}$ | 0.00 | 0.0002 | 0.05 | 0.035 | 0.007 |
| f % | 1.20 | 1.20 | 10.20 | 10.20 | 3.323 |
| m | 0.00 | 0.200 | 2.00 | 1.605 | 0.750 |
| $\beta$ | 0.50 | 0.50 | 1.00 | 0.994 | 0.773 |
| $\gamma$ | 0.50 | 0.50 | 1.00 | 0.978 | 0.896 |
| S m | 0.00 | 0.0031 | 0.50 | 0.400 | 0.230 |
| F-value after calibration | | 0.84 | | 0.86 | |
| F-value after validation | | 0.67 | | 0.72 | |

Simulated hydrographs show fairly good agreement with observed ones only for small peakflows, whereas simulation with the nominal parameters is much better. All happens as if the calibration forced the model to abandon SIDRA peakflow term (1 - $\beta/\gamma$) R(t). Introduction of a 2 hours time-lag and of a threshold of 0.25 l/s/ha on discharge data leads to an improvement of the F-value for validation and to a $\beta/\gamma$ ratio very close to the nominal one. Response surfaces for parameter combinations $K/L^2$ and $\beta$ (Figure 3a), $K/L^2$ and $\gamma$, f and $\beta$, f and $\gamma$, f and m show more or less circular hills, proving independance of parameters ; on the contrary, $K/L^2$ and f (Figure 3b), $K/L^2$ and m, f and m, and $\beta$ and $\gamma$, respectively, are dependant parameters. This means that the set of parameters related to soil hydraulic parameters ($K/L^2$, f and m) is independant of the set of parameters related to water-table shape ($\beta$ and $\gamma$). Reparemeterization leads to 3 parameters only, one being a combination of $\beta$ and $\gamma$, one being a combination of soil hydraulic properties, $K/L^2$, f and m, and one replacing the low sensitive parameter S.

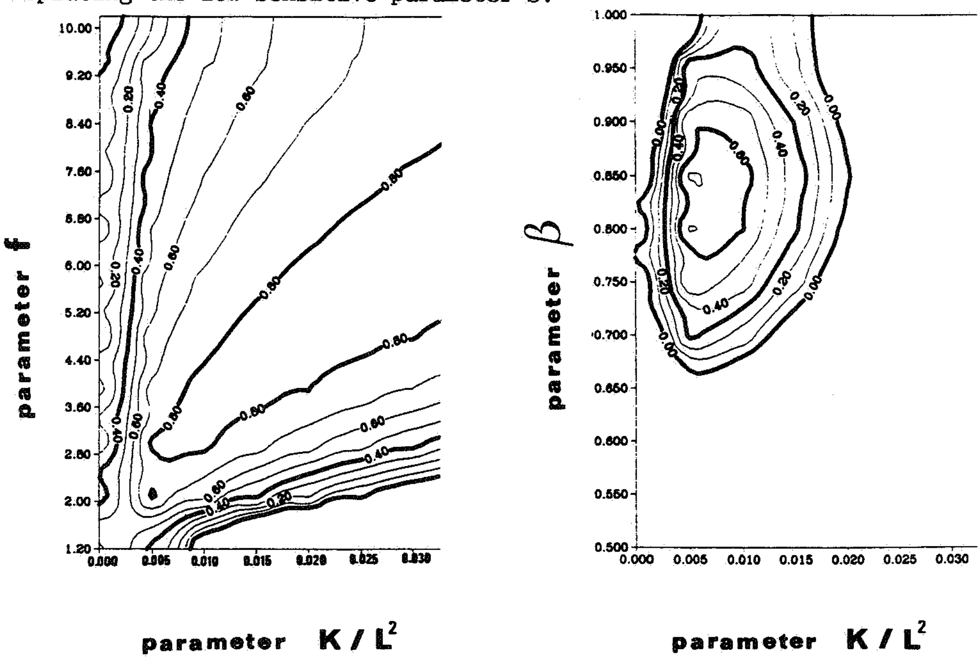


Figure 3. Response surface maps (F-values) for combination of parameters $K/L^2$ and f, and $K/L^2$ and $\beta$, respectively (a) and (b).
Data : 1980-1981 and 1982-1983. Time-lag = 2 hours.
Threshold = 0.2 l/s/ha

## 4 Calibration and validation of GR3

Initially derived on a daytime basis, GR3 has been adapted for running on hourly data. Calibration shows that several local optima exist. Whereas parameter B is quite stable, parameter A varies from 142 mm to 115 mm, and parameter C from 2 hours to 2.9 hours when starting the calibration from lower to upper bound initial sets respectively. The different local optima yield F-values greater than 0.8 on calibration ; the F-values decrease to roughly 0.7 on validation. Nearly all simulated peakflows are too low (Figure 4). Obtaining a unique parameter set for GR3 is difficult due to the existence of several optima which yield high F-values for calibration but low values for validation : the model parameters of the local optima are too much related to the characteristics of the calibration period, for this period is too short.

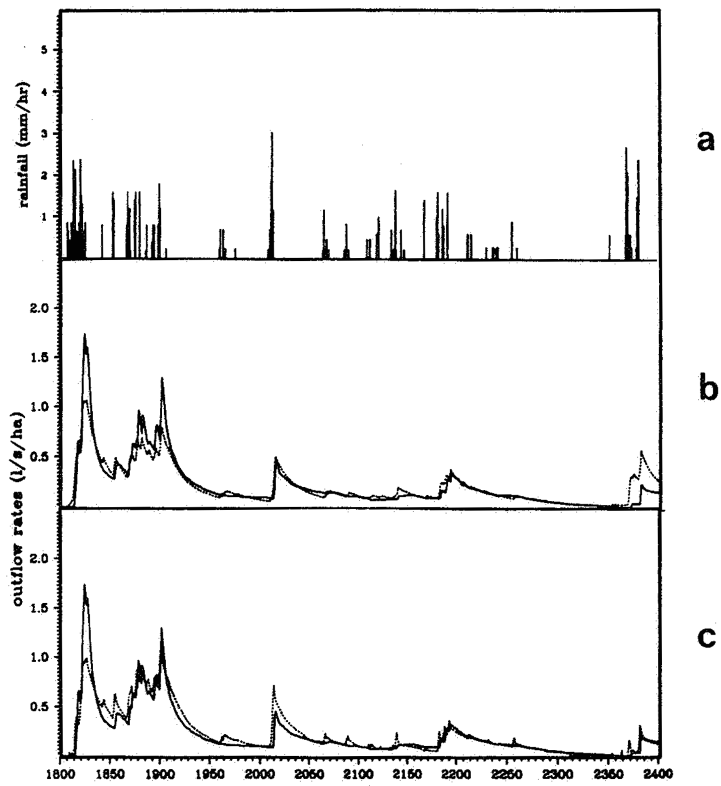


Figure 4. Sequences of rainfall (a), observed (—) and simulated (--) discharge rates with GR3 (b) and SIDRA (c) models.
Arrou, from 02/28/1981 to 03/24/1981

## 5 Discussion

Optimizing parameters of SIDRA, already measured by an independant deterministic method, gave insight into parameter redundancy problems. Two meaningful examples can be analysed. First, an error in a submodel - i.e. the time-lag in the unsaturated zone - can disturb estimation of another submodel parameter - i.e. transfer within the saturated zone. Second, the optimizing technique may make the wrong decision when two mechanisms are able to produce the same effect : peakflows can be generated either by the peakflow term of SIDRA or by the quadratic water-table height - discharge relationship, with, in the latter case, unrealistic values of the corresponding parameters. Another redundancy, hidden in the initial values of the state vector - the levels of the reservoirs - appeared in the attempt to fit GR3 out of its usual conditions of application, namely on less than one year continuous calibration period.

To cope with parameters redundancy, without using the water-table height data, SIDRA had to be reparameterized. As a result, the SIDRA transfer function is, except for the peakflow term, formally similar to GR3, and credibility of both models is somewhat enhanced by this convergence. Accordingly, GR3 and SIDRA may be used to evaluate the influence of drainage on water regime, the latter giving physical interpretation of the calibrated parameters of the former.

## 6 Conclusion

Convergence of a deterministic and a conceptual model does not mean identity, and, furthermore, is not compulsory for water management purposes, but leads to some important conclusions : 1) physically based models should not be optimized with a number of parameters beyond the capacity of data, and conceptual models should be kept simple ; 2) knowledge of physical meaning can help a clever, though subjective, optimization ; 3) drainage models developed in well-instrumented catchments, such as experimental and representative basins, may need reparameterization before being fitted with only one output variable, namely, discharge at the outlet.

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# QUANTIFYING THE HYDROLOGICAL IMPACTS OF A MAJOR ARTERIAL DRAINAGE SCHEME ON A 200 Km$^2$ RIVER BASIN

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## Abstract

Channelization schemes modify flow regimes, flood and low flow characteristics and the sediment loads of affected rivers. This paper highlights the results from a longterm, continuing study in which flow characteristics and sediment budgets of a channelized river have been monitored for a period exceeding ten years. Channelization marginally increases average daily flow and substantially increases mean annual flood. Hydrographs are more "flashy". Examination of detailed flood events gives some indication of the highly increased sediment loads associated with the production and readjustment of the new river channel.

## 1 Introduction

Land drainage has been a major feature of agricultural practice within the British Isles and mainland Europe for several centuries. As such its impact on natural river regimes is all pervasive and should not be ignored in the study of hydrological systems. Despite this, few longterm studies have been carried out on the influence of such engineering works on the quantitative changes that occur when a natural channel is channelized. Such channelization works result in the widening, deepening or straightening of the river and usually a combination of all three. The limited work that has been carried out has concentrated on the impact of channelization on flood peaks (Bailey and Bree,1980) and on total flow

(Essery and Wilcock, 1990). Such studies may result from the requirements of engineers to assess the possible consequences of channelization on the design safety and operation of engineered structures and on flood return periods. Disturbance of the natural river channel or of its surrounding land, however, may also enhance suspended sediment loads (Walling and Webb, 1987), which may in turn have important ecological impacts. In this paper, the effects of channelization on average daily flow, flood peaks and suspended and dissolved sediment loads are examined in an attempt to assess the impact of channelization on two different but related parts of the total river environment. This study cannot examine ecological impacts of channelization (Swales, 1982) but any quantification of changes in the physical river environment should be of significance for longterm ecological river studies.

## 2 Study Area and Dataset

The River Main (Figure 1) is a 205.8 $km^2$ catchment in which floodplain channel capacity was increased between 1984 and 1986 to improve arterial drainage and to contain flood events. The catchment is predominantly agricultural with approximately 72% being covered by grassland while 25% is covered by blanket bog in upland areas and by raised bogs in the central valley floodplain (Essery and Wilcock, 1986). Mean annual rainfall is 1400mm and mean annual potential evapotranspiration is 400mm. The catchment is instrumented for rainfall, evapotranspiration, ground water and stream discharge measurements. Since September 1980, continuous records of discharge are available for the Killagan, Cloghmills Water and River Clogh the three subcatchments which surround the floodplain. These tributaries are situated upstream of channelization works and serve as controls against which the effects of channelization can be assessed. The Clogh sub-catchment is used as the principal control in this paper as it occupies nearly half of the total study area and is therefore the most suitable for comparative purposes. Previous work examined the water balance and flow duration curves (Essery and Wilcock, 1990). Full details of instrumentation are given by Essery (1987).

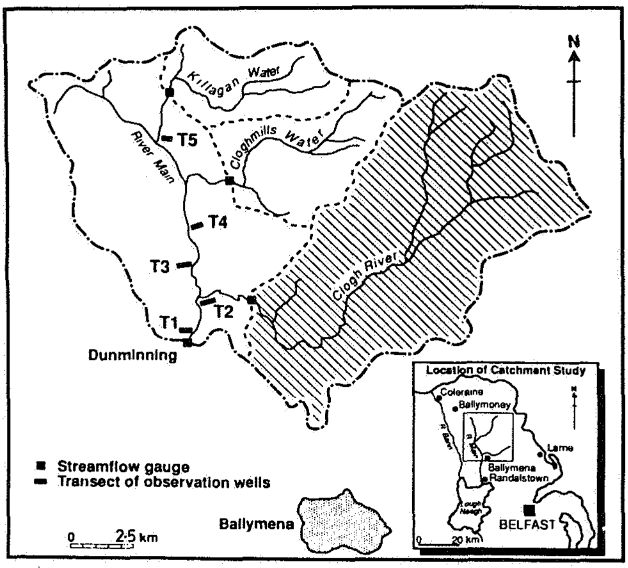


Figure 1. Location map showing study area and stream flow gauging stations

## 3 Impact on River Flows

The impact of channelization on flood peaks has been documented from various parts of the world, (Campbell et al, 1972; Keller, 1975; Bailey and Bree, 1980). In general, it can be expected that flood peaks will rise by as much as 100% and that such peaks will be achieved more rapidly as a result of improved hydraulic gradients. The River Main study reinforces these conclusions. Table 1 summarizes the impact of channelization on average daily flows (ADFs) and mean annual floods ($Q_m$). Mean annual flood peaks are derived from the peaks over a threshold (POT) method outlined in the Flood Studies Report, (NERC,1975). Table 1 also summarizes comparable data for the Clogh control catchment and obvious differences are apparent. While the River Clogh shows a slight decline in $Q_m$ (-6.4%) between the pre- and post-channelization periods, the River Main shows a 76.9% increase. This is in line with other studies and confirms the influence of improved channel efficiency on the production of higher peak flows. An interesting feature of Table 1 is that, prior to drainage, peaks

Table 1. Summary of changes in ADFs and $Q_m$ for the River Main and Clogh

| | | River Main Catchment | River Clogh Catchment | Ratio of Main and Clogh (%) |
|---|---|---|---|---|
| Pre-drainage (1980-83) in cumecs | ADF | 5.255 (5.608)* | 3.136 | 167.6 |
| | $Q_m$ | 30.412 | 42.079 | 72.3 |
| Post-drainage (1984-87) in cumecs | ADF | 5.686 | 2.922 | 194.6 |
| | $Q_m$ | 53.808 | 39.522 | 136.1 |
| % change | ADF | +8.2% (+1.0%)* | -6.8% | |
| | $Q_m$ | +76.9% (N/A) | -6.1% | |

(* excludes 1981/82, see Essery and Wilcock, 1990)

on Clogh sub-catchment were higher than in the Main catchment. This is explained (i) by the steep upland character of the Clogh, which encourage rapid runoff and (ii) by the pre-channelization capacity of the wide floodplain in the lower Main and its ability to attentuate floodpeaks. The augmentation of daily flows in the River Main as a result of channelization confirms earlier observations. The source of this additional flow is probably glacial gravels brought into hydraulic contact with the channelized river by dredging (Essery and Wilcock, 1990).

## 4 Impact on Sediment Budgets

During construction of the straighter, wider and deeper river channel, substantial quantities of suspended sediment were released, instantaneous concentrations reaching in excess of 1700 mg/litre. During the pre-channelization period on the River Main and for the total period of record on the Clogh, measurements of suspended sediment were obtained using a sampler based on the US DH-48 design, which was used at the 0.25, 0.50 and 0.75 width positions and with an integrated depth sampling cycle. On the Clogh, and for pre-channelization conditions on the Main, suspended sediment concentrations were relatively low (typically between 10 and 100 mg/litre). During, and following, channelization on the plain, sediment concentrations were high and variable, which resulted in very poor or non-existent rating relationships between sediment concentration and discharge. To overcome this problem an automatic event-driven sediment sampler was used to collect intensive sequences of suspended sediment and water quality samples for approximately 30 flood events at the Dunminning gauge (Figure 1) downstream of channelization works. Values from these were corrected to give equivalent depth/width integrated values by means of a regression equation using over 40 paired values.

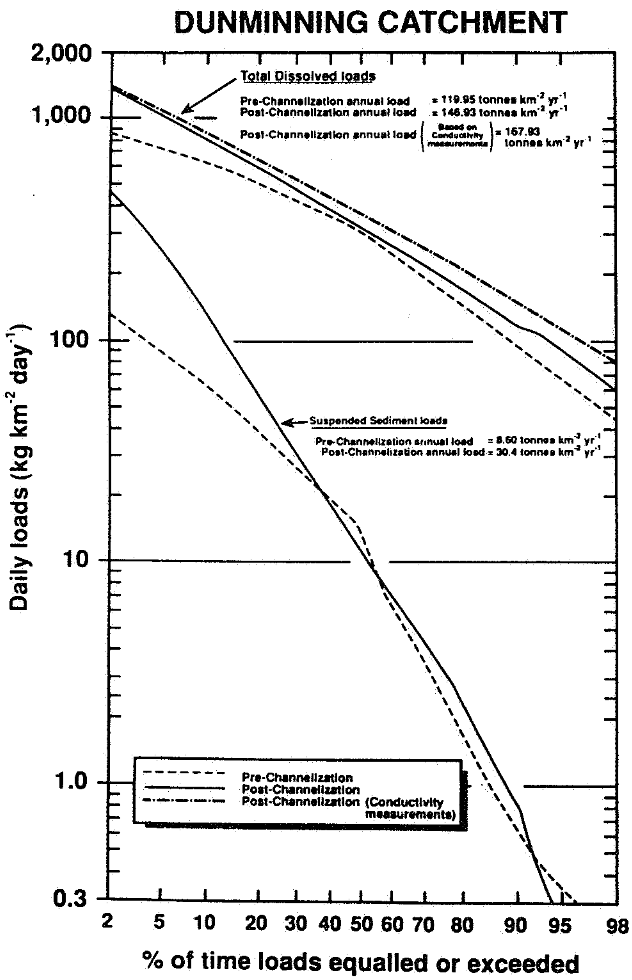


Figure 2. Pre- and post-channelization load duration curves for the River Main at Dunmining

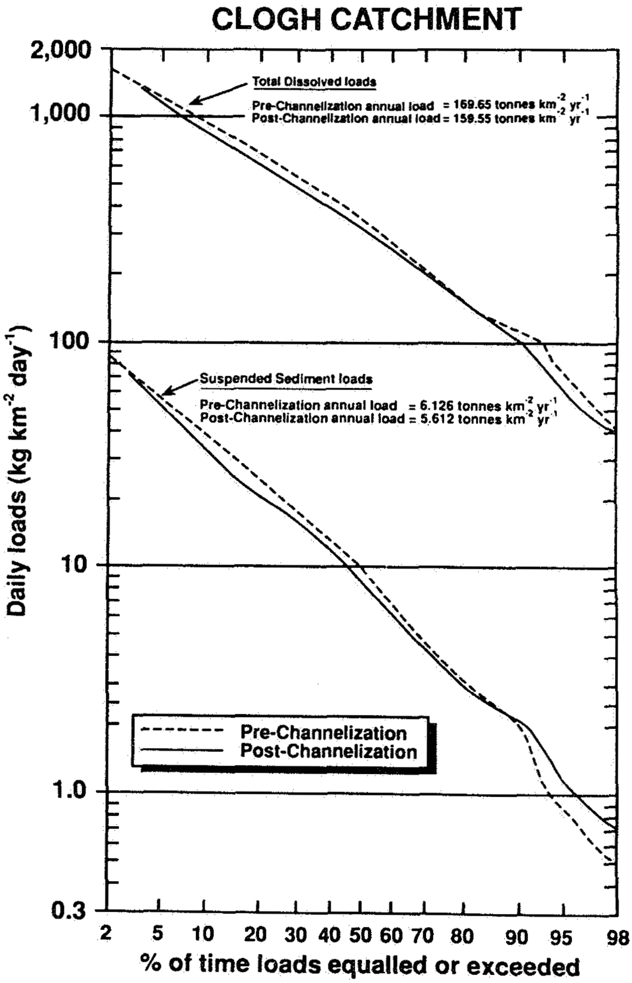


Figure 3. Pre- and post-channelization load duration curves for the River Clogh

As the relationship between suspended sediment concentration and discharge varied through the various stages of channelization, it was necessary to derive several suspended sediment/stream discharge rating equations which were applied to the three-hourly stream discharge values to produce daily and yearly mean loads. Figures 2 and 3 show "load duration curves" (LDCs) based on the daily estimates of suspended sediment load for both the River Main and the River Clogh respectively. On the River Clogh there is little change in the distribution and annual magnitude of the suspended sediment load between the two periods. Suspended sediment loads on the River Main, however, appear to be enhanced substantially by channelization. The enhancement of load is concentrated in the 2 to 40 percentile range, with only limited increases occurring at lower discharges. This illustrates the importance of high discharges in the entrainment and transport of newly released sediment. Data for the LDCs in Figures 2 and 3 are for the pre- and post-channelization periods and, as such, they tend to hide the extremities and annual variability over the four post-channelization years.

Figure 4 illustrates the temporal variation in total annual loads by expressing the annual loads relative to the volume of stream discharge for each year. This ratio remains virtually constant on the Clogh for the full

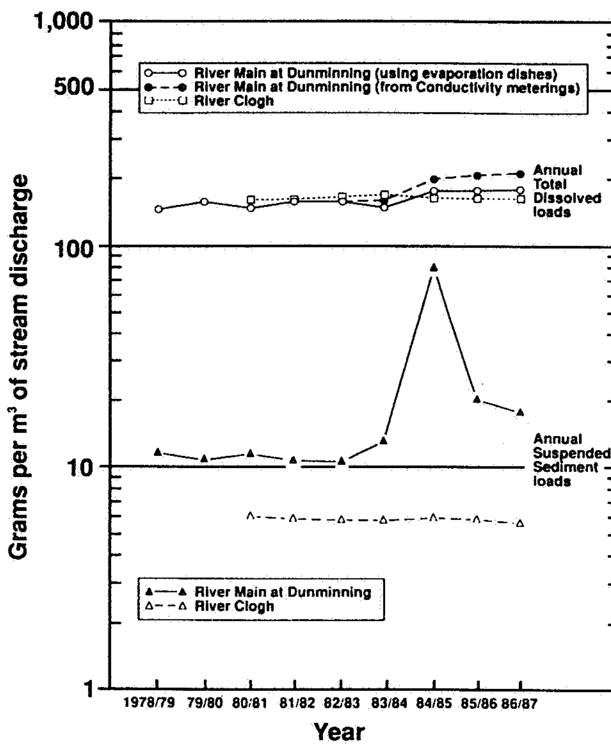


Figure 4. Variations in annual loadings of suspended sediment and total disolved load

7 year record. On the River Main the ratio substantially increases, most notably in the second year of channelization, when engineering works were most intensive and extensive. By 1986, most of the new channel had been excavated and sediment supply wasmarkedly reduced. Mean annual post-channelization suspended sediment load is therefore most likely best represented by the mean of data for 1985/86 and 1986/87 (15.8 tonnes/km$^2$/year)and not by the post-channelization four year mean (30.4 tonnes/km$^2$/year).

## 5 Impact on total dissolved load budgets

Total dissolved load was assessed in two ways: (i) by evaporation and drying of filtered water samples to give estimates of the total dissolved loads per litre of water, and (ii) for the post-drainage period by conductivity measurements on samples from an automatic sampler. Conductivity measurements were calibrated sucessfully as surrogates of total dissolved loads. Figures 2, 3, and 4 summarize changes in total dissolved loads for the River Main and River Clogh in a similar format to that of the suspended sediments. Again changes appear to have occurred in the River Main following channelization. Similar changes over the same time period are not apparent on the Clogh.

The increase in total dissolved load increases on average by 22.5% ( by 40% if the conductivity data are used). Three factors, separately or in combination, most probably explain the increase.The first is enriched groundwater flow from the confined glacial gravels in the River Main floodplain, now tapped as a result of channel enlargement. A second factor may be reduced floodplain storage in the River Main floodplain following channelization. Before channelization, the combined streamflow from the three tributaries exceeded streamflow at Dunmining resulting in frequent overbank flooding of the fen and marginal raised bog in the floodplain of the River Main. It is possible that the higher dissolved load inputs from the Clogh in pre-channelization conditions (170 tonnes/km$^2$/year compared to 120 tonnes/km$^2$/year for the Main) reflect absorption of some of the dissolved loads in the floodplain materials of the Main. Following channelization, floods are more easily contained within and more rapidly flushed through the River main channel. This more rapid fushing and the reduced contact time between flows from the tributaries with the floodplain deposits and vegetation probably partially explain the non-absorption of dissolved loads following channelization. A third possible factor is increased fertilizer/slurry use following channelization in the lower Main. Given the present low uptake of field drainage in the area following channelization, this is the least probable explanation of the enhanced dissolved loads since 1984.

## 5 Conclusions

The river now experiences more extreme flows, is more heavily laden with suspended sediment (especially in flood events) and has an increased dissolved load. These changes have ecological and geomorphological implications. It is important to establish if impacts observed to date are maintained indefinately. The monitoring continues.

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# THE RESULTS OF LONG-TERM MEASUREMENTS IN FOUR CARPATHIAN BASINS

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Abstract

The importance of long-term time series of measurements for the evaluation of the precipitation-runoff relationship and of the water balance in small forested basins is illustrated in two representative basins in Czechoslovakia, where research has been carried out since 1927, and also in two experimental basins, where work has been in progress since 1953. It is always necessary to take climatic fluctuations into account because of their interference with other external impulses to the ecosystem. No significant consequences for long-term runoffs have been established in connection with the afforestation of the basin to 36.5% nor with the modern wood harvesting technologies and low intensity of forest damage by air pollution. The runoffs increased in only one of the basins studied, where air pollution was more severe, and forest renewal over 2/3 of its area and a change of wood species (beech to Norway spruce) took place. The long-term changes of streamflow regime are effectively dampened by natural compensating mechanisms. It would not, therefore, be correct to claim that conclusions from short-term measurements could be extended to climatically different regions.

## 1 Introduction

In Czechoslovakia, hydrological research in forest environments has been carried out for more than 60 years. The best known results of this research are based on measurements made by Valek (1959, 1962) since autumn 1927. Following a method used in Switzerland, he measured the precipitations and water runoffs in two hilly basins: Kychova (KY, area 4.27 $km^2$) and Zdechov (ZD, area 4.09 $km^2$). KY was fully forested, but only 4.6% of the ZD basin was covered by forest.

Water consumption in Czechoslovakia is continuing to rise, and it is therefore necessary to establish whether, in mid-european conditions, it is possible to intervene in the forest growths so as to increase water yields. For this purpose, two experimental basins were set up in Mala Raztoka (MR, 2.07 $km^2$) (Fig. 1) and Cervik (CE, 1.85 $km^2$) (Fig. 2).

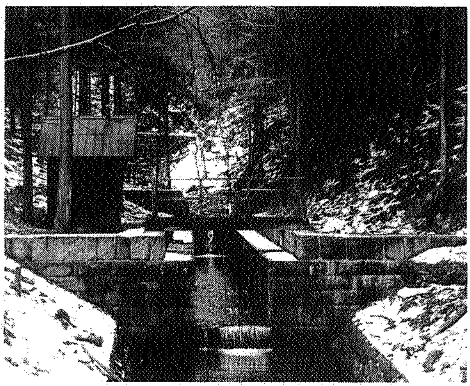

Figure 1. Gauging drain for measuring runoffs in Mala Raztoka

Figure 2. The view of the Cervik experimental basin

All these basins lie on the NW foothills of the Carpathian range between 482 and 1084 m a.m.s.l. The streams of MR and CE are only 10 km apart, KY and ZD are separated by 25 km of MR and CE. They should give conclusive data on the water dynamics of the eco-system in comparable natural conditions not only during the gauging period but also in relation to their changes during the period of growth renewal in both experimental basins (MR and CE) including substitution of beech by Norway spruce (MR) and to damage due to air pollution. The measurements

measurements are still in progress.
The measurements of bulk precipitations in MR and CE between 1981 and 1987 showed inputs of 40 kg S/ha a and 17-25 kg N/ha a.
The gaseous short-term concentrations of air pollutants are stronger in MR than in CE, with the result that the forest in MR has been more severely damaged (Jarabac and Chlebek, 1988).

## 2 The basins

The basins at MR, CE and KY are fully forested. At the beginning of these researches, the basin of ZD was forested over only 4.6% of its area. In the 1950's, it was afforested on a further 31.9%; the recent average age of the forest is between 20 and 40 years. The MR and CE basins were calibrated between 1953 and 1965. Since 1966, renewal of the forest has been in progress, using the technique of clearing and replanting the forest in strips. By the end of 1989, 2/3 of the MR and CE basins had been renewed. Because CE is naturally divided into a Y-shape in two parts (A, 0.88 $km^2$ and B, 0,84 $km^2$), a method of paired comparisons is used. Intensive renewal of the plantations is being carried out in part A; by the end of 1989, 95% of part A had been renewed (Fig. 2). The main characteristics of all the basins were described earlier by Valek (1962) and Jarabac and Chlebek (1988). The characteristics of the precipitation-runoff relationship are listed in Table 1.

## 3 Results of analysis

The analysis of measured data was directed to testing whether the sum of runoffs has been influenced by forest changes during the last 61 (36) years. The effects on single elements of water balance such as interception and infiltration, of vegetation changes arising from forest renewal or forest decline due to air pollution, are considerable. However, only their aggregated effect is of practical use in making possible an increase in water yield.

Table 1. The relationship r = a + bP

| Basin | | ZD | KY | ZD | KY | CE | MR |
|---|---|---|---|---|---|---|---|
| | | 1928 - 1953 | | 1954 - 1988 | | | |
| P | mm | 894 | 1006 | 849 | 893 | 1137 | 1243 |
| Pmin | mm | 663 | 756 | 618 | 640 | 756 | 842 |
| Pmax | mm | 1224 | 1386 | 1089 | 1135 | 1447 | 1871 |
| cvP | +- % | 17.2 | 16.9 | 14.3 | 15.6 | 16.3 | 17.1 |
| R | mm | 487 | 479 | 452 | 443 | 632 | 903 |
| Rmin | mm | 237 | 240 | 190 | 154 | 361 | 519 |
| Rmax | mm | 758 | 690 | 665 | 679 | 885 | 1438 |
| cvR | +- % | 30.9 | 29.5 | 26.9 | 24.8 | 22.7 | 27.1 |
| R/P = F | | 0.54 | 0.45 | 0.53 | 0.50 | 0.56 | 0.73 |
| P - R | mm | 407 | 554 | 397 | 450 | 505 | 340 |
| a | | -312.9 | -295.5 | -223.5 | -130.4 | -139.6 | -11.1 |
| b | | 0.89 | 0.77 | 0.80 | 0.64 | 0.68 | 0.74 |
| rRP | | 0.92 | 0.93 | 0.79 | 0.82 | 0.88 | 0.64 |
| cvRP | +- % | 12.7 | 11.5 | 16.9 | 14.7 | 11.1 | 21.5 |

Linear regression provides the simplest model for the precipitation-runoff relationship. The linear relationship R = a + bP between yearly runoffs R and precipitations P in the basin ZD is shown in Figure 3, with crosses and rings representing the time segments 1928-1953 and 1954-1988 respectively; the calculated 95% confidence limits area also shown. The position of the regression lines is the same in both time segments, but the later time period is characterized by a greater scatter of the data. Two values exceed the confidence limits. The main statistical characteristics are listed in Table 1, where f is the runoff coefficient R/P, P-R is the water loss, r is the correlation coefficient and cv the coefficient of variation.

The relationship between yearly runoffs R from the basins ZD (y) and Y (x) is presented in Figure 4 and its statistical characteristics are listed in Table 2. The relationship between $R_{ZD}$ and $R_{KY}$ is more closed than the precipitation-runoff relationship in Figure 3.

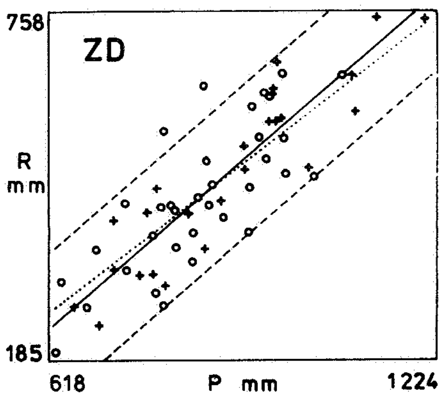


Figure 3. The relationship R = f(P) in the Zdechov basin

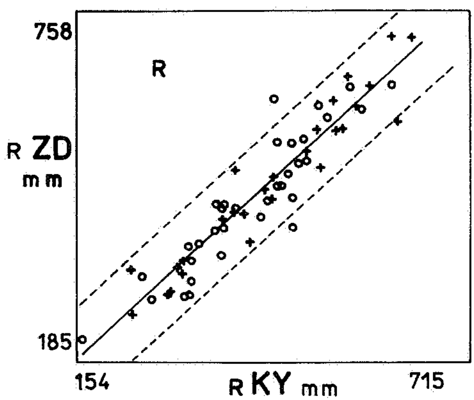


Figure 4. The relationship $R_{ZD} = f(R_{KY})$

Table 2. The relationship $R_{ZD} = a + b (R_{KY})$

| Time segment | $\bar{R}_{KY}$ mm | $\bar{R}_{ZD}$ mm | $\bar{R}_{ZD}-\bar{R}_{KY}$ mm | a | b | r | cv % |
|---|---|---|---|---|---|---|---|
| 1928-1953 | 479 | 487 | 8 | -0.7 | 1.02 | 0.96 | 9.4 |
| 1954-1988 | 443 | 452 | 9 | 2.5 | 1.02 | 0.91 | 11.2 |

The yearly water loss P-R in the basin ZD during 1928-1988 is shown in Figure 5. This loss occurred in evident climatic cycles similar to those showing the consequences of wood fellings as described, for example, by Hibbert (1967), although in ZD there has not been any clearcut effect. It is also necessary, therefore, to allow for the possibility of runoff changes due to climatic fluctuations in short-term forest hydrological experiments and the 30 year of measurements seems as yet too short for this purpose.

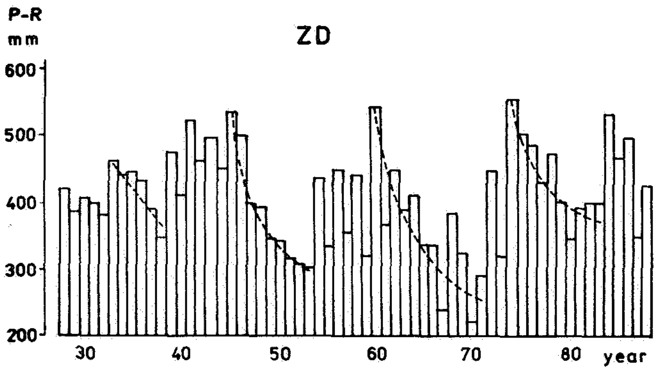


Figure 5. The water losses (P-R) in the Zdechov basin

The R/P regression lines from the four basins are compared in Figure 6 and their statistical characteristics are listed in Table 1. The MR basin lies on the windy NW slopes of the main range and experiences heavy rainfalls. The sequences of the runoffs from the basins MR, CE and KY are shown in Figure 7 (the runoffs of KY and ZD overlap, see Table 2).

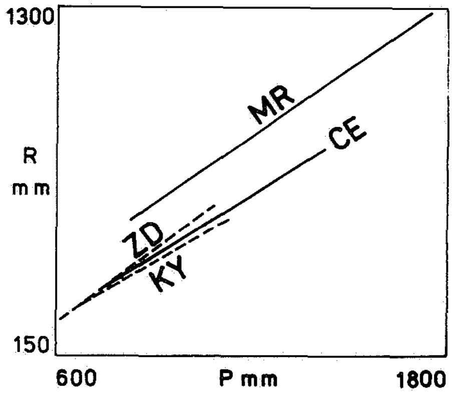


Figure 6. The precipitation-runoff relationship in four Carpathian basins

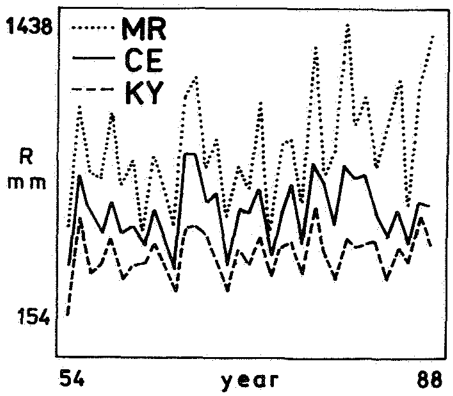


Figure 7. The sequence of the runoffs from the basins examinated

The sequences are evidently influenced by the climate of the area, but in the MR basin it is noticeable that there has been a significant water yield increase in the last 10 years. This is confirmed by the double mass curve shown in Figure 8.

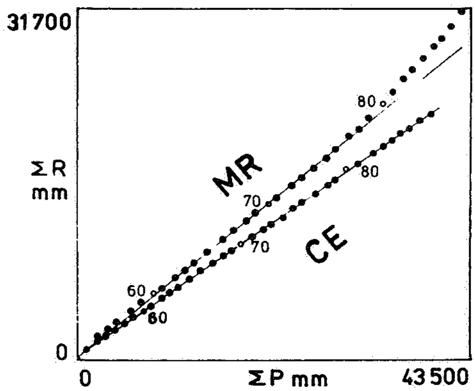


Figure 8. The double mass curve between precipitations and runoffs in the MR and CE basins

While the relationship is linear in CE during the whole period of the measurements, it becomes non-linear in MR in the 1980's. It is not possible to explain this effect in terms of the whole year data, because the time segment is too long for it. Analysis of the cool and warm periods of the year showed that the homogeneity of the time series of winter precipitations and summer runoffs had been disturbed. The snow on bare slopes is subject to intensive drifting. Its water equivalent cannot, however, be exactly measured. The cause of increased water yield in MR during the last ten years in the warm season of the year cannot be conclusively established in this way because of possible effects of:

- advanced forest renewal with changes of wood species from beech to spruce;
- ecosystem weakening due to long-term air pollution;
- other, so far unknown, influences.

The double mass curve in Figure 8 cannot yet be used to predict where an increase in water yield may be anticipated and put to practical use.

## 4 Conclusions

Some research results from two representatives and two experimental basins in Czechoslovakia, with long-term measurements in comparable natural conditions, are described in this paper. The analysis of the data from these basins showed the necessity of working long-term measurements in order to separate climatic fluctuations from the consequences of other causes; primarily changes to vegetation cover. This is very important because the fluctuations can be large enough to mask runoff changes and thus lead to invalid research conclusions. It has been found that in basins where the water consumption is fully supplied by rainfalls every year, the streamflow changes might be only of long-term and modest character. Neither the forest increase by 30%, nor the forest renewal using the methods of modern harvest technologies, caused any significant change to the streamflow regime. The streamflow increase in one of the basins examined can be explained as a consequence of the subdued evapotranspiration caused by the wood species change or of ecosystem weakening due to air pollution.

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# EFFECTS OF CLEARCUTTING ON HYDROLOGICAL REGIME IN THE JIZERA MOUNTAINS, CZECHOSLOVAKIA

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## Abstract

Industrial emissions have caused large scale changes in the vegetation cover in the northern highlands of the Czech Republic. More mountaineous areas will be affected in such a way if the contamination of the atmosphere will continue. It is most important to elaborate an exact evaluation of the present and future rate and regime changes of the stream flows in the deforested watersheds.

## 1 Introduction

Withering and clearcutting of monoculture spruce forests damaged by acid rains and by the following infestation helped calamagrostis villosa to spread substantially on mountain plateaus and hill slopes of the headwaters. The success rate of reforestation by substitute tree species is low due to the unfavourable climate. This reality has to be taken into account to ensure the demands of the watermanagement.

## 2 Jizera Mountains region

The Jizera Mts. belong to the Krkonose-Jizera granite massif. Their central part, most affected by forest damages, is a protected territory with natural water accumulation. On an area of 100 square kilometres their heights range from 700 to 1000 metres. Their economic: wood production, water supply and tourism.

## 2.1 Climate

| | |
|---|---|
| Mean annual temperature | 3-4.4° C |
| Vegetation season | 150 days |
| Annual precipitation | 1300-1800 mm |
| Rainy days per year | 200 |
| Average height of snow cover | 100-150 cm, duration November-April |
| Maximum daily precipitation | 341.5 mm in July 1987 |

## 2.2 Atmospheric pollution

Main pollutants: $SO_2$, $NO_x$, compounds of Cl, F, Al.
Maximum wet deposition in headwaters: 31-39 $t.year^{-1}.km^2$, 1985-1987.

## 2.3 Forestation

95-99% of the catchment areas are forest lands.
Age of the forests investigated in the area of 100 $km^2$:

| | | |
|---|---|---|
| 1983 | clearings | 1.6% of the area |
| | 1-10 year old stands | 11 % |
| | young and middle age forest | 28 % |
| | adult and old stands (partly withering or dry) more than | 50 % |
| 1987 | clearings | 9.7% of the area |
| | 1-10 year old stands | 21 % |
| | some smaller catchments cleared of | 25-70% |

reduction of forest land by construction of roads and wood stores is 0.23% of the forest land in 1983

1989 smaller catchments are completely deforested;
in unaccessible localities dry stands remain uncut; reforestation by spruces and substitute tree species proceeds continuously with a partial success; prevailing vegetation cover is calamagrostis villosa.

## 2.4 Erosion

The shallow soil cover on a granite base is composed of brown forest soil, partially waterlogged and peaty. Clearings and wood transportation by heavy machinery caused erosion on hill slopes in the tracks and driveways.

Erosion survey in 1987 in the area of 48 $km^2$:

| | |
|---|---|
| number of erosion trenches | 46 |
| length | 19 km |
| eroded volume | 40 ths.$m^3$. |

The denudation of bolders and the sheet erosion still increases.

## 2.5 Hydrological regime

1951-1980

| | | |
|---|---|---|
| two gauging stations, watershed areas of | 25 | $km^2$ |
| mean annual specific discharges | 38 | $l.s^{-1}.km^{-2}$ |
| minimum runoff | 3 - 4 | $l.s^{-1}.km^{-2}$ |
| basic subsurface flow | 10.8-13.6 | $l.s^{-1}.km^{-2}$ |
| hundred-year-floods specific discharge | 6.5- 5.5 | $m^3.s^{-1}.km^{-2}$ |
| minimum monthly discharges | September, February | |
| maximum monthly discharges | April, May | |

## 2.6 Water quality

pH 4,5-5,5 after liming of the area
3,1-4,5 during snow melting in 1987
waters of total mineralization 70% (27-40 $mg.l^{-1}$)

main components:

$SO_4$, $NO_3$, CL together 64% of total mineralization

$Al^{3+}$ 2-3% of total mineralization

maximum concentration of $Al^{3+}$ 4.45 $mg.l^{-1}$ in April 1987

## 2.7 Watermanagement

Three reservoirs of total volume 33 $mil.m^3$, management rate 1 x year; watersupply for drinking water and industrial use 550 $l.s^{-1}$; flood protection and electricity-production.

# 3 Formulation of problem

The big scale changes in vegetation cover of basins cause changes of hydrological regime and runoff rate that is necessary to take into account in the hydrologic data elaboration for the watermanagement and design of water-works.

## 3.1 Background knowledge

The first difficulties how to estimate hydrological changes after clear-cutting appeared in 1978 when serious forest damages necessitated a protection of open-pit coal mines in the Krusne Mts. foothills against flooding. A group of 20 Czech and Slovak hydrologists, based on their experiences and literature, came to different conclusions in solving the problem: for completely cleared forests, the derived values of increase in 100-year flood design characteristics ranged from 20 to 300% of the original value of a peak discharge; the increase of annual runoff of 600 mm ranged from 0 to 80% of the original value of annual runoff. The final agreement was to increase the values of 100-year flood peaks of 5 to 15% respective to every 10% clearing of the forest area in basins. The percentage varied with respect to an assumed success of the reforestation. For the annual and seasonal runoff changes the conclusion was a mere "there might be significant changes".

At that time Ministry of Forestry and Watermanagement recommended to start with the monitoring of hydrological changes in the Jizera Mts., where a deterioration of the forest vegetation health in the near future was anticipated.

## 3.2 Networks in the Jizera Mts.

Climatological and hydrological monitoring is provided in the area of 100 km².

Number of stations:

2 meteorological stations with air pollution measurements
1 Alpine station monitoring a limited number of climatological components, air pollution and wet deposition
12 raingages, 23 pluviometers
9 watergauging stations, watershed areas from 1,5 to 25 km²
36 localities for snow depth and water value measurements, both in forest and on clearings
10 localities for a random waterquality measurement.

## 3.3 Influences upon runoff in deforested basins

The parameters effecting runoff are well known but it is difficult to quantify their share in the runoff change from the whole basin. They mutually interact and more over their effects on the runoff are often to a high degree contrary:

- reduction of horizontal rainfalls, increase of rainfall amounts reaching the ground;
- reduction of evaporation from substitute vegetation species, increase of evaporation from snow cover;
- good infiltration conditions of calamagrostis villosa through a dense root system, dash roof effect of calamagrostis villosa in heavy rains and rapid snow melting;
- change of the snow depth distribution over the watershed area caused by wind effects, gradual decrease of the snow depth and water value on clearings due to the sun effects increasing snow evaporation and

infiltration to soil under the snow cover, lesser water stores in snow in the end of winter, increase of the snow melting rate and runoff speed in spring;

- increase of the soil density on clearings, increase of the soil clogging by sheet erosion, preserving the reference ways of infiltration by stumps left in the ground on clearings;
- increase of the drainage net length in the basins, increase of water accumulation in depressions caused by reforestation and tracks movements on peaty soil;
- drying of peaty bogs, wetting of hill slopes.

### 3.4 Change in long-term average annual runoff

Most of the recent foreign studies confirm that after deforestation the annual runoff increases significantly. In Czech research works Vaverkova (1982) gives an increase of 8% in the average annual runoff at the time of an intensive deforestation. A very important indication based on a long-term monitoring in the Beskydy Mts. gives Jarabac (1983). Even after clearing of 84% of the watershed's area the likely runoff changes were within the fluctuation range of the climatic parameters.

Practically the same results obtained Bubenicková (1987) in the Jizera Mts. Skopek (1988), too, finds no visible runoff changes in the deforested watershed in the Krkonose Mts.

Kantor (1987) helped to clarify the differences between the Czech and foreign results in his evapotranspiration studies of ground vegetation. After clearing an increase of 100 mm per year may be expected at most and only for a short period after the deforestation. In former studies by Kantor and Sach (1982), too, the depth of the runoff from a spruce forest compared with grass vegetation and young stands differs about 140 mm at annual rainfall of 757 mm.

The above mentioned examples show that up till now no marked increases of the annual runoff in the basins concerned have arisen compared with results from experimental basins abroad. The reasons for this fact might be (Bubenicková, Kasparek, 1989) the following:

- the experimental basins abroad are mostly of an order smaller than the ones in the Czech mountains;

- in experiments the clearing is made all at once. Sometimes the basins are then retained vegetation free. The clearcutting in forests damaged by emission is made stage by stage. It lasts always several years and deforested localities are scattered all over the watershed area;
- at the time when spruces are becoming dry the undergrowth of calamarostis villosa spreads and that helps to form a very substitute ground cover on clearings even if the reforestation is not entirely successful;
- the rainfall frequency is very advantageous as even a one month period without rain is very uncommon.

To asses the actual changes of the runoff it is necessary to present the rainfall and runoff data in the natural conditions prior deforestation in millimetres. Any percentage value may lead to wrong applications. There is a big difference if a runoff change of 100 mm occurs in a basin at the foot of the mountains with an annual runoff depth of 300 mm or with one of 1200-1400 mm at the headwaters in the mountains.

The increase of the annual runoff in the Jizera Mts. after deforestation is not substantial and, moreover, it is only temporal. It is not recommended to take it into consideration in watermanagement practice and design.

### 3.5 Annual frequency curve changes of daily discharges

In our natural conditions the frequency curve of daily discharges is dependent mainly on the intensity of the rainfalls and partially on the hydrogeological structure of the watershed. The character of these two components do not change through deforestation so it may be assumed that the annual frequency curve of daily discharges do not change significantly by deforestation, too.

This finding is supported by the results from the Beskydy Mts. given by Jarabac (1984) and the Jizera Mts. (Bubenicková, 1988). This fact is favourable as the decrease of 300- to 364-day discharge values assumed in some previous studies might have had very difficult consequences not even for the water supply but for the ecology of rivers and brooks, too.

## 3.6 Changes in seasonal runoff distribution

From a hydrological point of view the seasonal runoff changes are not the most fundamental ones but they are the only demonstrable changes (Bubenicková, 1987).
Considerable changes occur in spring due to the acceleration of the runoff caused by snow melting. The average monthly discharges in March and April increase at the expense of discharges in May and partly in June. The total runoff volume caused by spring snow melting decreases due to a partial melting in winter time and higher evaporation from snow cover on clearings. No other significant changes have been proved in the following months of the vegetation period.

## 3.7 Changes of maximum discharges

Owing to the stochastic character of the evaluation of the maximum discharges it is difficult not only to forecast but the less to prove their possible changes. The experiences from Krusné Mts. indicate that even though the reforestation of the clearings was not fully successful and had to be renewed, the substitute tree species (mountain-ashes, birches, etc.) together with a dense calamagrostis villosa cover of the watersheds ensured not only an effective retention and infiltration of rainfalls but a good stabilization of the watershed against erosion, too. And so, even if the forecast of deforestation has fully come true, there have not been observed any significant increases of floods or sheet erosions in the localities with a substitute vegetation.
The Jizera Mts. are more sensitive to a potential erosion compared to the Krušné Mts. due to their geology, steep hill slopes and heavy rainfalls. The main danger for the discharge to increase is at the time of the forest clearing when the heavy machines solidify the soil and form on hill slopes new drainage ways through tracks and roads. A very

dangerous situation may arise even without any change in the flood regime when in the river flow drifting hewed trees form and break barriers.

A statistical analysis may disclose only with difficulty the change of flood discharges owing to the random occurrence of floods. More reliable results can be obtained by an analysis of the watershed response. The research studies by Krejcová (1988) for the watershed of the Smeda river in the Jizera Mts., proves that the sensitiveness to clearing is only a fraction of the very sensitive response related to rainfall intensity and amount.

Though the question of the maximum discharges in watersheds after deforestation is far from being solved, in the last few years we have succeeded in progressing from the merely theoretical calculations based on empirical equations to a deeper knowledge of the actual flood discharges. For example at a very extreme rainfall event on the Jilovsky brook in the Krušné Mts. in 1987 (runoff depth 123 mm, max. specific discharge 6.6 $m^3.sec^{-1}$, watershed area 18 $km^2$) only a half of the rainfall amount flew off in the form of direct runoff. The infiltration ability of the partly oak forest, grass land and partly substitute vegetation watershed cover on emission caused clearings proved to be very effective. The vegetation cover acted favourably in protecting the watershed from erosion too, but the channel erosion was enormous.

In hydrological assessments of flood discharge changes in different regions affected by industrial emissions it is necessary to stress the differences in geographical and climatological conditions and from these ensuing differences in flood regimes, flood volumes and peaks.

The research in this field is far from ready. Moreover, the sporadic occurrence of extreme rainfalls in the last decades has been very advantageous for flood protection but less useful for the hydrological studies of floods.

## 4 Conclusions

The studies made clear that due to the variation in the natural conditions of different areas damaged by emissions the mere applications of knowledge without deeper analyses may not be correct. Moreover, the applied clearing and reforestation technology is important by itself for any decisive results.

The change of flow regime in larger basins in the mountaineous areas with forests damaged by emissions is not as profound as expected, mainly due to the catchment's substitute vegetation cover.

In the future the effort has to be focussed on a detailed analyses concerning the forming process of a flood runoff and on the estimation of changes in infiltration characteristics caused by soil degradation.

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# INFLUENCE OF WATERSHED LAND COVER ON RUNOFF HYDROGRAPH

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Abstract

A mathematical model has been used for simulating the rainfall-runoff process in a small mountain watershed in Carpathians. Six basic hydrological subprocesses, which significantly influence the rainfall-runoff relationship have been taken into account in the model. Results of model application for predicting hydrographs for the watershed with variable land cover are presented.

## 1 Introduction

Field measurements in experimental watersheds usually aim at collecting data, which are used for identification and verification of mathematical models describing different hydrological processes, and for estimating the relationships between chosen elements of hydrological cycle.

Field investigation of time-areal-distribution of rainfall, interception of forest and agricultural plants as well as evapotranspiration, infiltration and runoff have been carried out in an experimental watershed of Trzebunka. Trzebunka watershed, showed in Figure 1, is located in Carpathians, South Poland, about 30 km south of Cracow.

The watershed area amounts 30.4 km². Forest area was decreased in the past ten years from 16.4 to 13.3 km² i.e. of about 10% of the watershed

watershed area. The watershed has an absolute relief of 563 m. Loam and sand loam are dominating soil type. The mean annual precipitation in Stroza gauging station is estimated at 1016 mm.
A mathematical model has been developed to assess the influence of land use on runoff hydrograph.

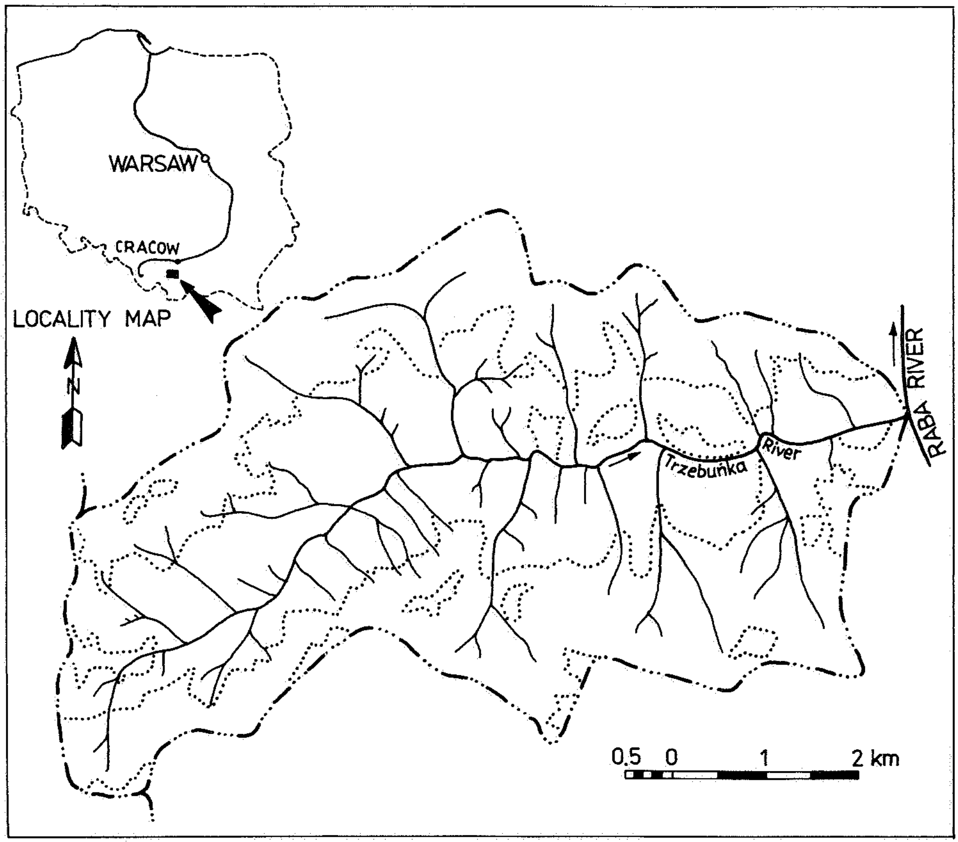


Figure 1. Trzebunka watershed

## 2 Description of the model

The structure of the model is based on the SHE model (Bathurst, 1980). The rainfall-runoff relationship has been described by six basic hydrological processes, which significantly influence the time-areal distribution of runoff. The processes were as follows; interception, evapotranspiration, infiltration, base flow, surface runoff and flow in streams. The components of the model are shown in Figure 2.

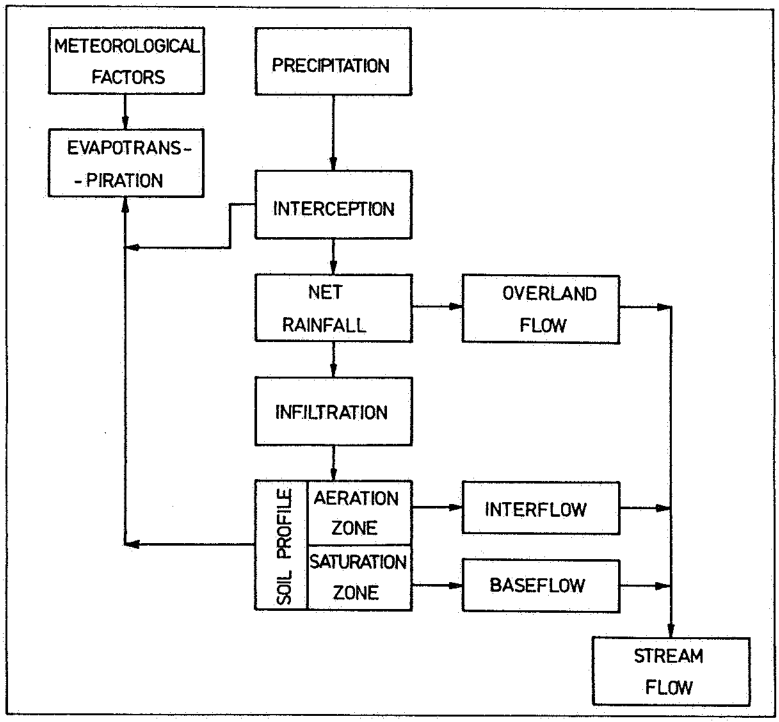


Figure 2. Schematic picture of the rainfall-runoff conversion

The process of interception is described by the model of Rutter (Eagleson, 1970). Values of interception depend on type of plants and canopy cover, and hydrometeorologic conditions, which influence evaporation from free water surface. Evapotranspiration is the other process taken into account in the integral rainfall-runoff transformation model. The process has been analyzed as evaporation from plants i.e. transpiration, and evaporation from soils.

The actual value of evapotranspiration has been computed from the model of Penman-Monteith. The value is dependant on temperature and moisture of air, wind speed, solar radiation, soil moisture and land cover. The evapotranspiration influences directly soil moisture changes through absorbing by plants water from root zone. Equation of Richards (Eagleson, 1970) describes changes of soil moisture and negative pressure. The soil moisture changes depend on soil type, and type and density of canopy. The actual amount of water in soil profile is determined by relationship between soil moisture and negative pressure.

During the time when intensity of net rainfall is higher than infiltration rate, surface runoff occurs. For the description of the surface runoff the Kinematic Wave equation and continuity equation have been used. The same equations have been employed for the computation of flow transformation in the river network. In the non-rainfall periods the depth of groundwater table is estimated from one-dimensional equation of Boussinesque. More detailed description of the model is given by Osuch et al., (1982).
The above described model has been used, after calibration based on measured data, for assessing response of watershed with changed land cover, to rainfall.

## 3 Example of the model application

In the first stage the model parameters have been fitted based on multipeaked event from Trzebunka Watershed of May 2-6, 1979. Forest covered 54% of the watershed area at the time. In the second stage the model with the known values of its parameters has been used for estimating the response of the watershed to the same rainfall, assuming different area of forest in the watershed. For computation, it has been assumed that forest covers 10%, 40% and 75% of the watershed area respectively. Results of computation are shown in Figure 3.
The model seems to be a useful tool for assessing the response of the watershed with different land cover to rainfall.

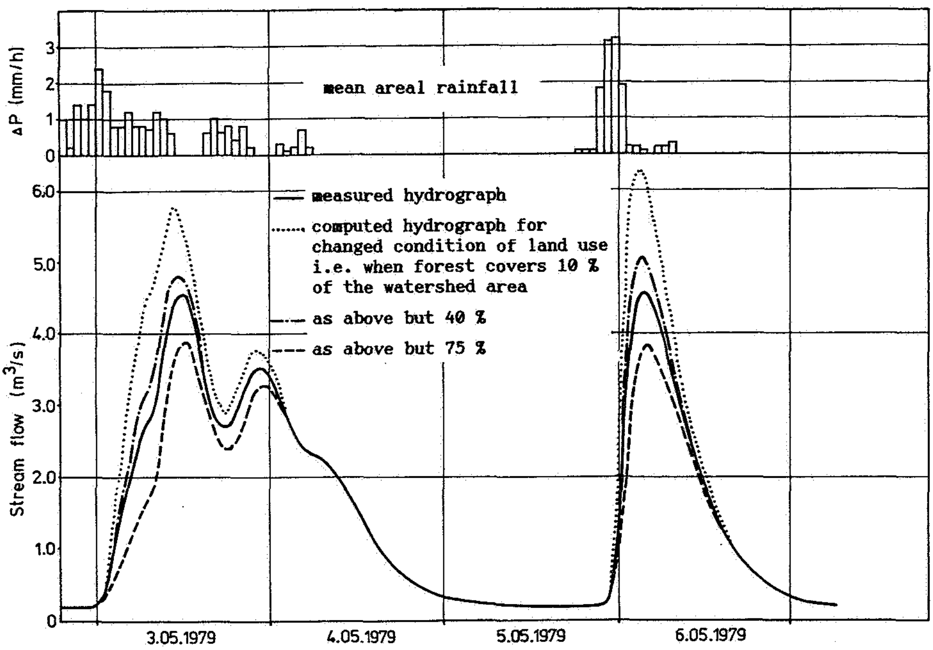


Figure 3. Hydrographs for present and changed land use conditions in the watershed

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# THE EXPERIMENTAL CATCHMENT
# OF THE SPUTKA RIVER

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Abstract

On the Sputka Catchment (104.3 km²) dimensionless unit hydrographs were derived using the PICOMO program (Dooge and O´Kane, 1977) and the individual events were compared in the shape factor diagram. The shapes depend strongly on the space-time characteristics of rain which would probably overshadow effects of man-made changes in the catchment. For modelling scenarios on the upper forested part of the catchment the threshold model for total runoff, based on API functions, with three rain inputs, CLSX (Todini, 1980) was used. The scenarios of the reduction in transpiration showed small or no change in the streamflow maxima of big events or events on the wet catchment. On the contrary, the increase in maximum streamflow due to the simulated soil compaction kept in the same proportion regardless of the magnitude of event and the antecedent conditions.

## 1 Introduction

A number of Czechoslovak mountain catchments are menaced by deforestation due to air pollution. In most cases the changes in the vegetal cover took place before sufficiently detailed regular measurements have been established. Therefore almost no data exist on which it would be possible to compare the period before and after the change. In the beginning dramatic changes in the magnitude and shape of flood hydro-

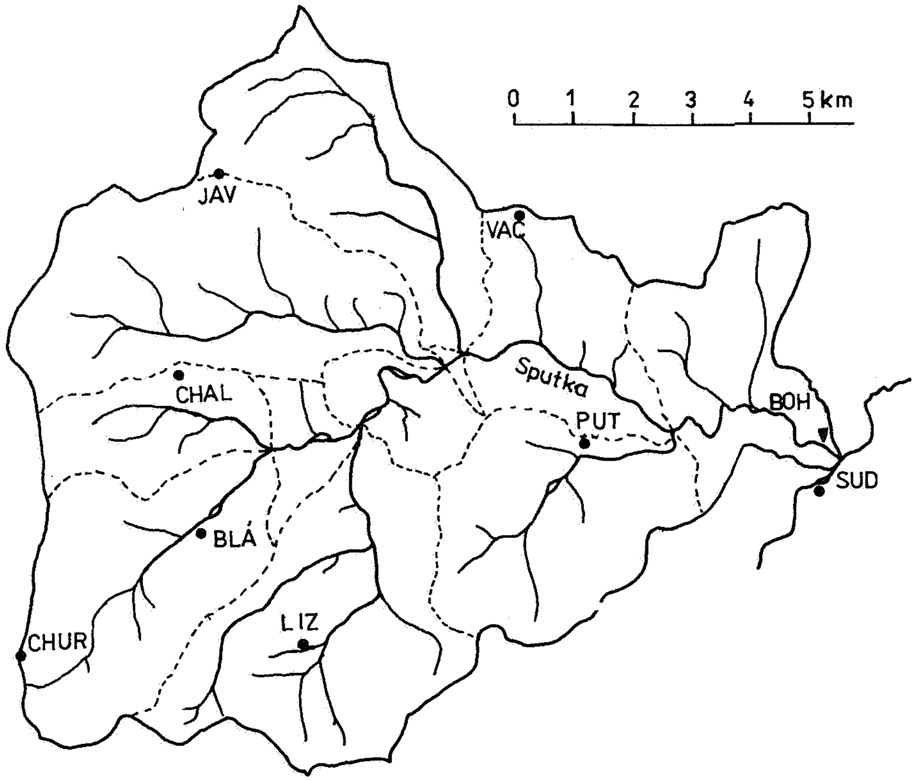


Figure 1. The Sputka Catchment

graphs were feared. It showed, however, that the vegetation, which by natural way substitutes the original forest, largely fulfils its functions as to promoting the infiltration capacity, preventing erosion etc.

The Sputka experimental catchment (104.3 km²) is situated in the Šumava Mountains where no consequences of air pollution could be distinguished till recent times. The measurements started during the period of IHD and have been subsequently carried out by several different institutions for various purposes, particularly rainfall-runoff modelling, research into water balance elements, such as the soil moisture, interception, evapotranspiration etc.

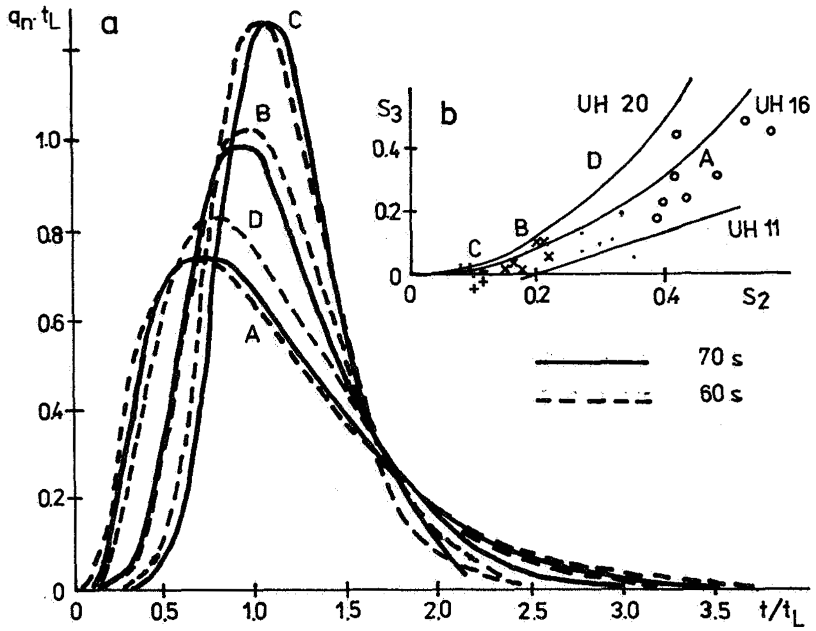


Figure 2. Dimensionless unit hydrographs of UH 16 (a) and shape factor diagram (b) ($S_2$, $S_3$ - second and third shape factors)

So far the Sputka Catchment, where detailed investigations are available, has been regarded as a catchment with stationary conditions. In the forthcoming period, however, some changes may be expected.

## 2 The Sputka Catchment

Geologically the Sputka Catchment is composed of fissured igneous and metamorphic rocks. As to the vegetal cover, 39 % of the area is forested, 48 % under grass and pasture, 13 % is cropland.

In Figure 1 the location of the measuring stations can be seen. For the modelling reported below the discharges at BOH station and the rainfall measured at SUD (555 m a.s.l.), VAC (740 m a.s.l.) and CHUR (1122 m a.s.l.) were used (Janoušek and Mates, 1980). Soil moisture was observed with the help of tensiometers at 20, 40 and 60 cm at PUT station (characterizes the soil zone of 500-700 m a.s.l.), LIZ, BLÁ and CHAL stations (700-1000 m a.s.l.) and JAV station (above 1000 m a.s.l.). At LIZ there were also two lysimeters, one with bare soil and the other with grass making it possible to compute the soil water balance. The top 30 cm of the soil are regarded as essential for the description of the soil moisture conditions of the catchment. The average field capacity is equal to 130 mm (Janoušek and Mates, 1980).

## 3 The shapes of unit hydrographs

The shapes of flood hydrographs from the 1960s and 1970s have been compared by way of the dimensionless unit hydrographs (UH) derivation and by the shape factors (Dooge, 1977, Dooge and O´Kane, 1977). Each of the dimensionless UH A, B, C, D has been obtained from two to five events and each of them represents a family of curves in the coordinates $q_n$, t ($q_n$ - normalized direct runoff, t - time) differing only by $t_L$ (lag of the catchment). The $t_L$, however, does not depend on the rainfall intensity but rather on space-time characteristics of rain. The groups A, B, C, D themselves also depend on the rain characteristics: A - longer rain, approximately uniform in space, B - shorter rain, heavier in the upper part of the catchment (CHUR), C - complex hyetographs and hydrographs, D - small events (peaks about 1 to 6 $m^3 s^{-1}$) otherwise similar to A. The shape factors of events A, B, C, D are shown in Figure 2b together with the curves representing the Nash model (UH 16), the convective diffusion reach (UH 20) and the scalene triangle (UH 11). The overwhelming importance of the space-time rainfall pattern would most probably overshadow changes in the flow regime if the causal changes in vegetation took place only on a small part of the catchment. The method of the multiple-event identification (Brüen and Dooge, 1984) yielded similar results.

## 4 The modelling of scenarios

Having in mind both the importance of rain variability and the fact

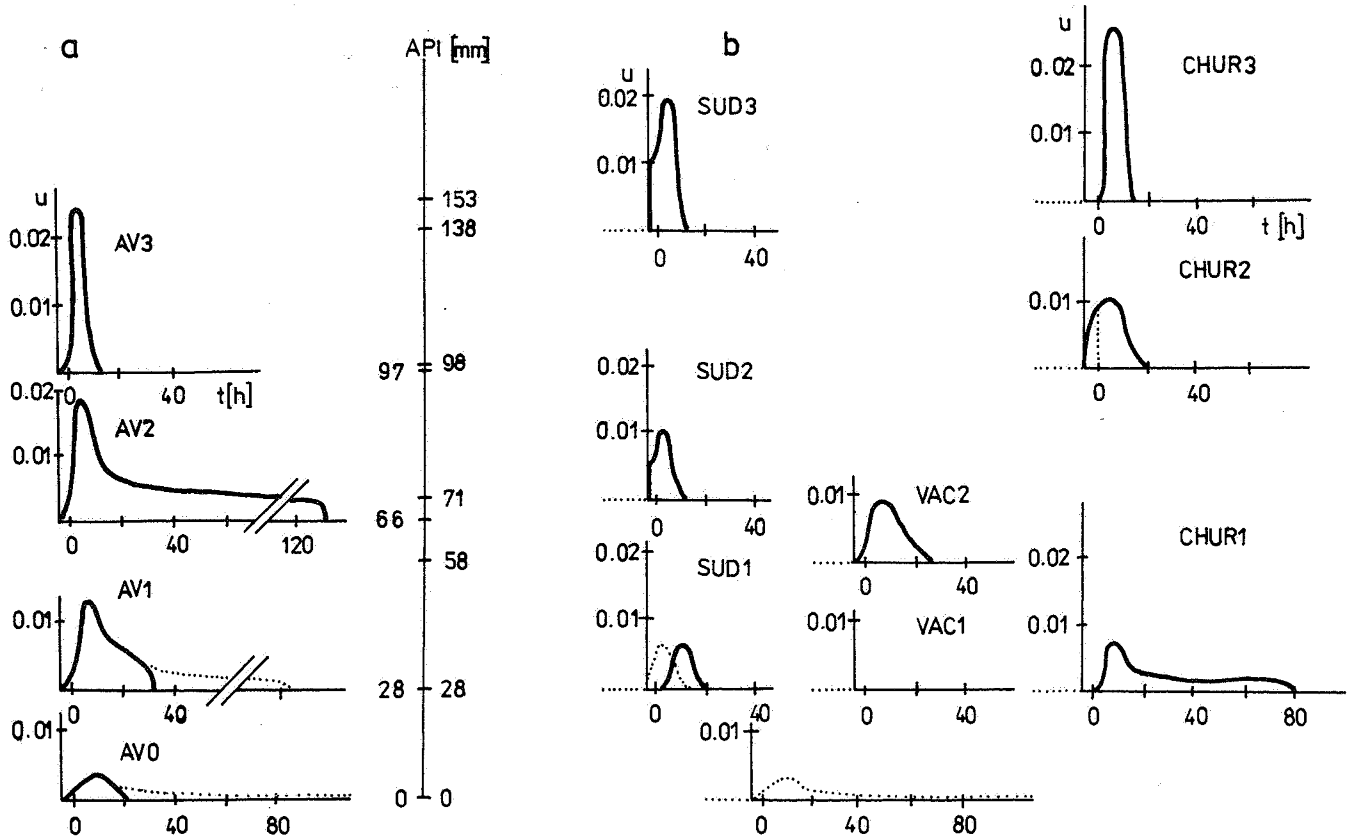


Figure 3. Schematic diagram of the impulse-response functions (u) of the CLSX model with areal average (a) and three rain inputs (b) (API - antecedent precipitation index; dotted lines - corrections to apply)

that the potential changes in the vegetal cover imply in the first place changes in the soil moisture subsystem the nonlinear time-variant model for total runoff CLSX (Todini, 1980) has been chosen for further analysis. The results of the calibration with both the areal average and three rain inputs were discussed by Blažková (1990) and are shown here in Figure 3. For comparison, the soil moisture content at LIZ station was for AVO at 106.9 mm under bare soil and 96.9 mm under grass, for CHUR3 at 130.1 mm and 124.5 mm, respectively.

The set of parameters with the three rain vectors was used for modelling scenarios. All of them took place on the part represented by the CHUR station (forested). Two types of changes were simulated:

- TRANS - reduced transpiration due to the dying of forest which leads to the increased soil moisture; It is modelled by lowering the values of the thresholds in CHUR by 20 mm (-20) and by 60 mm (-60). The model would switch to a higher response function sooner;
- COMP - soil compaction due to rough logging practices which leads to a decrease in infiltration; It is modelled by increasing the response functions at CHUR linearly 1.3 times (1.3) or twice (2) (at CHUR1 only the first 12 hours).

The antecedent soil moisture patterns were the following:

- DRY - no antecedent rain;
- M.WET (mildly wet) - derived from the 100-year three-days and two-days maxima of rain after subtracting the two-days and one-day maximum, respectively, and distributed uniformly in time and non-uniformly in space (isolines by Kulasová et al., 1985);
- WET - obtained by repeating the scenario with M.WET and the appropriate rain for the second time after one day without rain.

The causal one-day rain, again non-uniform in space, with the return period of N = 0.5 to 10 000 years was distributed to 4 (4h), 8 (8h) or 12 hours (12h). In Figure 4, $q_c$ denotes the runoff (mm) modelled with the calibration parameters and $q_s$ (mm) the runoff modelled with a set of parameters simulating change. For better orientation the 100-year flood $q_{100}$ is indicated.

The results of the TRANS scenarios (Figure 4 a, b, c) are in agreement with the results of many studies having used the paired catchment method and summarized by Swindel and Douglass (1984). The maximum of their curve is at the return periods smaller than N = 0.5 (Figure

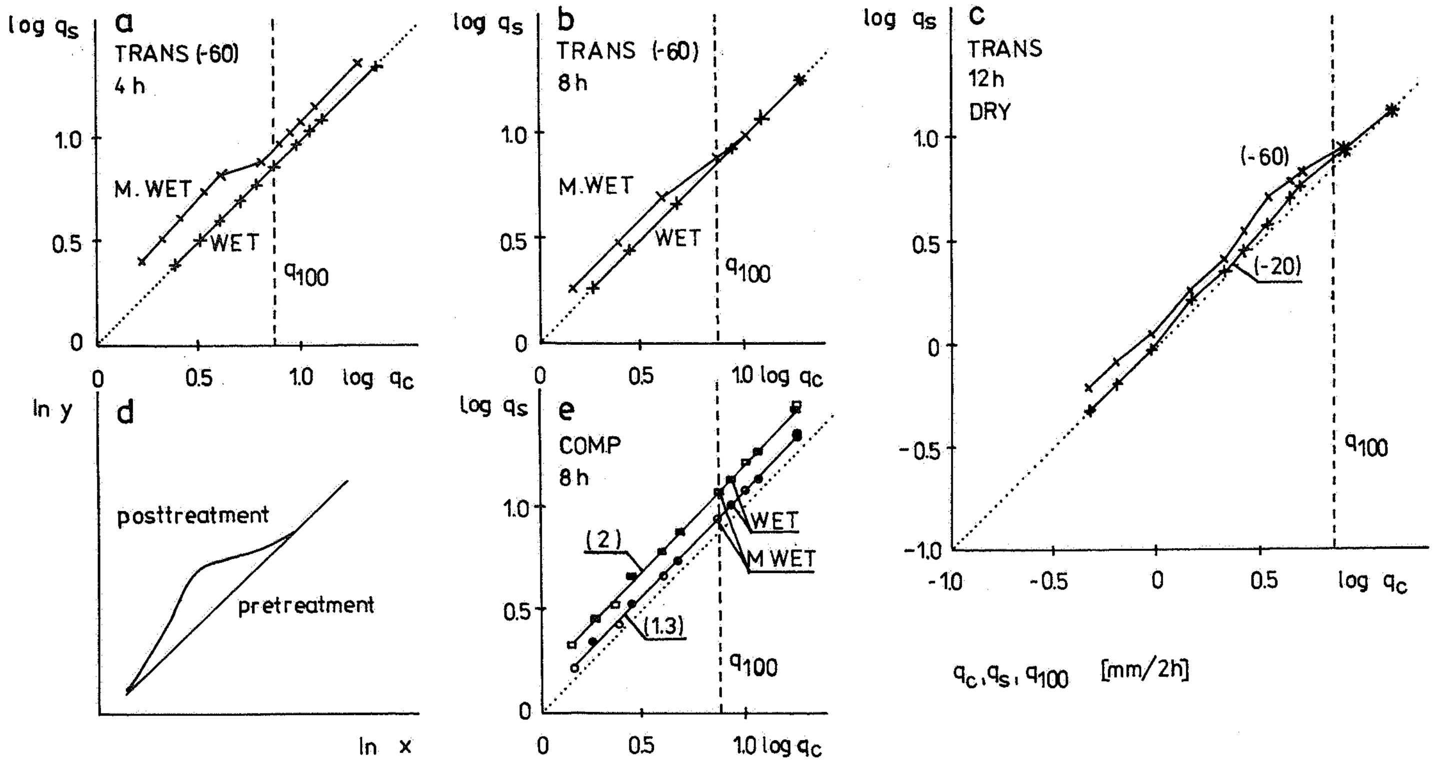


Figure 4. Modelling scenarios at CHUR in the Sputka Catchment (a, b, c, e) and comparing them with a postulated and proved relationship on a paired catchment data by Swindel and Douglass (1984) (d) (x, y - runoff on control and treated catchment, respectively)

4d). In the Sputka Catchment only the asymptotic descending part has been computed. For big events and events on wet catchment there is not much change in the magnitude of floods before and after the change in vegetation.

In case of the COMP scenarios the changes in streamflow look almost linear, i.e. they keep a similar proportion for smaller and bigger events and for the mildly dry and wet catchment (Figure 4e).The increase in per cent is, however, smaller than the change in response functions. By doubling the ordinates at CHUR we get only about 1.6 times bigger streamflow.

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# EXPERIMENTAL AND REPRESENTATIVE BASIN STUDIES IN CHINA - A 35TH ANNIVERSARY REVIEW

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Abstract

Three stages of basin studies are summarized briefly. After experienced a development of runoff experimental stations widely covered regions with different natural conditions directed largely towards problems of engineering hydrology, now the basin studies in China have to turn most attention to the problems of water resources development and protection. Facets of basin studies are briefly reviewed: the runoff process research dealt with improvements on the computation methods and, exploration of a new designed artificial experimental catchment using nuclear techniques. Several examples are given of anthropogenic impact studies as the effects of engineering works, agriculture, urbanization and afforestation. However, some concepts on experimental and representative basins that seem problematical, are discussed, as well the inadequacy of natural basins for some hydrological studies.

## 1 Historical and present situation

### 1.1 Beginning

The first experimental basin in China was set up by the Yellow River Conservancy Commission in 1943 at Liangjiaping near Tianshui, Gansu Province. The Largewillow Brook (Daliushugou) with a drainage area of about 0,49 km² is a typical cultivated loess basin with gullies sloping

up to about 15%. It was set up for the study of the effects of soil and water conservation engineering practices on water and sand yields.
However, the first actual hydrological basin study in China was commenced in 1953 to study the effects of agricultural drainage from different drainage moduli on surface and subsurface runoff. Seven catchments with areas ranging from 2.49 $km^2$ to 162.4 $km^2$ were instrumented with a precipitation and a groundwater table observational network until 1956.

## 1.2 Expansion and development

Guidelines for field hydrological research and experimental network planning were completed by the Institute of Hydrology from 1956 to 1958. Three kinds of stations, different from conventional hydrologic stations were defined as the runoff station, runoff experimental station (RES) and hydrological experimental base with different scientific demands and therefore hydrologic items to be monitored. However, the runoff station type was cancelled in 1978 and the work of experimental base did not start before 1978. In the period 1956-58 a lot of Chinese hydrological basin studies of the type RES were set up: 21 RES, 3 for soil and water conservation, and 1 for reservoir studies. These basin studies were distributed over 16 provinces and various climatical and geomorphologic regions of our country. This period seems to be a golden era of the basin studies in China.
In these years, hydrologic research was directed largely towards improvement and development of methods for hydrologic computation and prediction including volume and rates of flow and erosion losses, based upon the understanding of hydrologic processes in various physiographical environments and under different anthropogenic activities. So, within and after this period, the main approach of research was that of so-called major representative stations, which were selected carefully to have a good representation of environments in a broad physiographical region. The selected watersheds covered as far as possible a complete range of physical conditions in this area. In general, several small watersheds were included in the RES serving as representative and experimental catchments. Approaches adopted in

our studies were: typical watersheds, paired watersheds and bench-mark watersheds. Paired or bench-mark runoff plots were used to study the runoff-coefficient.
Unfortunately, most of these stations were substantially gone with the wind until 1978. This decline covers just the period of IHD, while the role of representative and experimental basins was emphasized.

## 1.3 Period of transition

Up to now, several agencies in this country are responsible for hydrological basin studies. A field experimental base, situated to the north of Yantze river was set up in 1978 by the Chuzhou Hydrology Laboratory of the Institute of Hydrology and Water Resources. Field research of this base aimed to develop experimental investigations of hydrological events and processes, as well as component studies of the hydrological cycle and their interactions under various combinations of natural and anthropogenic factors and effects. A further aim of the base is the experimental investigation of hydrological problems in rational water resources development and protection. It includes: fundamental studies in experimental catchments and lysimeters, a precipitation network of China for isotopic monitoring within the IAEA/WMO global network; applied studies in temporary instrumented experimental stations, situated in Inner Mongolia, Jiangxi Province, etc. As comparative studies, several RESs belong to the provincial Bureau of Hydrology co-operating with the base, namely:

- Baogaidong RES, Hunan Province, forested mountainous humid region, 1.2 to 22 $km^2$, founded in 1958;
- Wulumuqi RES, Xinjiang Autonomous Region, high mountain area with glaciers in semiarid region, 7.2 to 308 $km^2$, founded in 1978;
- Yebaishou RES, Liaoning Province, Loess hilly in semiarid region about 0.06 to 2 $km^2$, founded in 1958.

Except these, several RES are distributed in other provinces belonging to the provincial Bureaus of Hydrology, e.g., Jiangwan of Zhejiang Province, Binxian in Heilongjiang Province, etc. The Yellow River Conservancy Commission still supports three experimental stations for soil and water conservation studies including Tianshui as mentioned above.

Now, in basin studies more attention is devoted to hydrological problems related to water resources evaluation and development instead of engineering hydrological problems as dominated in early stages. And, more attention is also devoted to the mechanism of hydrological processes instead of empirical comparisons. So, in the meantime, it is clear that basin studies in China meet its transition period following the transition of modern hydrology from engineering to water resources research. The concepts and research methods effective in early stages are faced with serious challenge. May the basin study proceed with this situation? It is very important to change old concepts, to introduce new methods and, to introspect the strategical basis and tactical approaches adopted in early stages.

At present China has 52 experimental basins distributed over 11 provinces: 10 in mountainous and 25 in hilly regions, 7 in plain areas and 10 on a loess plateau. There are 313 representative basins distributed over 24 provinces. However, it should be pointed out that the term experimental basin is used to designate any watershed established in the RES which remained now regardless of its present working condition. The term representative basin is used to designate all the basins which role has been demonstrated recently in regional runoff research and covering drainage areas equal to or less than 100 $km^2$.

## 2 Fundamental research of runoff processes

The general situation of runoff process studies using information from RESs or concepts, gained directly from experiments conducted in experimental catchments, is as follows:

a) Improvement of runoff generation modelling. In early stages, information of runoff factors was used to get better rainfall runoff relations, using rainfall intensity, index of moisture storage, average groundwater level, etc., as parameters. Afterwards, more attention was attracted by using basin averaged infiltration capacity combined with initial losses, referring to the basin moisture content or groundwater level. Subsequently some empirical equations were derived. Recently, theoretical examination in combination with experimental results have been resulted in mathematical models. For example a model (Wen, 1982) has been constructed combining two types of infiltration curve with the area distribution curve reflecting the non-uniformity of infiltration capacity within the basin. This model has been verified mainly from the RES in arid and humid zone.

b) Nonlinear regularity of IUH parameters. Nonlinear response to rainfall intensity was demonstrated, i.e., no definite value of $m_1$ in the Nash model can be expected for a basin, as it is inversely proportional to rainfall intensity and amount of runoff.

c) Improvements on geomorphological IUH. A general equation of geo-IUH for any order of river was derived and, the dynamic factor, velocity, can be determined by special designed methods.

d) Spatial variation of runoff factors. It is demonstrated that even in very small catchments the spatial variation of runoff parameters should not always be overlooked. A case study from intensive measurements of soil moisture by neutron probes, both in the wet and dry season have shown that the spatial variation of soil moisture content conforms a normal distribution. The distribution curves of evapotranspiration from land surface and of the infiltration parameter S in Philip's equation measured by nuclear techniques, have the same pattern (Gu, 1987).

e) Natural tracer studies on runoff generation. In an artificial catchment, surface runoff, interflow from unsaturated zone and groundwater runoff from the saturated zone have been identified. Four different patterns of interaction between those components have been defined according to the composition of components (Gu, 1988). From the del values of $^{18}O$ and or TU in these components, it is found that in most cases, pre-event old water dominates volumetrically the runoff in our catchments. The different patterns of interaction as mentioned above meet different ranges of old water, in extreme conditions it reached 36% to 86%. In a natural forested representative basin, we also found that old water contributed about 65% to 80% to the river flow. A further isotopic verification of runoff we were surprised that old water may enter into the overland flow in the form of condensed pre-event vadosewater even in a very small catchment. This proportion in our work for example reaches 50% as the maximum.

However, the current rainfall runoff relation which is widely used in this country implies all of the event rainwater, get from hydrograph separation, comes from overland runoff and, every point sited on the rainfall runoff scatter-diagram implies that it refers one and only one event. This concept seems to be in a great doubt.

# 3 Research on anthropogenic impacts

## 3.1 Effects of engineering works

### 3.1.1 The effects of drainage system in a plain region

Impacts on annual runoff were investigated from the change in evaporation E and its composition, e.g. data from a watershed of Blue Brook showed that E from groundwater diminished after drainage, E from soil surface supported by losses of rainfall increased, E from depressions decreased, E from vegetation increased of better grow, total E of this basin decreased, and annual runoff decreased with round 20%. However, the discharge modules M increased. Several empirical equations were derived and it was shown that M is proportional to the net rainfall to be drained, within the designed frequency of drainage system, and inverse proportional to the drainage area and density of drainage network. These equations were used for drainage design in the plain regions, which have to be drained according to social-economic conditions.

### 3.1.1 The effects of reservoir

The impact on annual rainfall was studied, e.g. a case study from Xinanjiang showed that on north of it, there was a 100 mm maximum decrease of annual rainfall up to about 70 km from the reservoir. However, rainfall increased to the south with a maximum of about 100 mm up to about 60 km from the reservoir. At the center of this reservoir a 11% decrease, about 150 mm, was found. The impact on flood processes was also studied. It is found that floods entering the reservoir are quite different from those under natural condition at the same site (flood at the dam site). A case study of Fengman showed that $Q_m$ of floods entered will be about 30% greater than that of floods under same rainfall conditions without dam.

## 3.2 Effects of soil water conservation works in loess region

A case study from paired watersheds (Wangliagou) showed that in a 15 years period with annual mean precipitation of 545 mm, the annual mean runoff from a terraced and afforested basin and an untreated basin was 17.4 mm respectively 34.4 mm and the annual erosion was 10 100 ton/km$^2$ and 20 000 ton/km$^2$, respectively.
Concerning erosion factors, it was found that total the erosion depth is proportional to the surface gradient to an exponent greater than unity and, to rainfall intensity i. However, it was also found that when i is less than 0.3 mm/min, erosion may decrease as surface gradient increased. E.g. the 12 years annual mean of erosion on runoff plots (Suide) had a significant increase from 773 to 5 617 ton/km$^2$ when plot gradients vary from 8°34' to 28°41', however, decreased to 2.386 ton/km$^2$ when the gradient increased to 34°20'. A critical slope length was also found, i.e. when the slope length is less than the critical value, runoff decreased as length increased.

## 3.3 Effects of agriculture

Basin studies of irrigation water use in a semi-arid region showed that water use in the upper reaches may lead to a deterioration of water quality and ecology in lower reaches. E.g. for Yuanyangchi Basin at the Taolai River, annual mean runoff entered this basin from 1959 to 1968 had a 8.1% decrease due to water use mainly for irrigation. Hydrochemical anomaly of phreatic water within this basin was changed from $SO_4$ type to $SO_4$-Cl type and salinity increased to 2-3 g/l. Salinity of confined water was changed too, and increased from 658.5 mg/l to 1 640.4 mg/l in a typical well for drinking water supply. This deterioration affected the drinking water of about 30% of people.

## 3.4 Effects of urbanization

A case study showed that runoff coefficients of industrial, agricultural and mixed districts are related to the spatial structure of open water as well that of permeable, semipermeable and impermeable surfaces in the area. Unit hydrographs of pollutants in different areas are different from each other and the monthly amount of pollutants drained from different districts are related to runoff with different patterns (Wen, 1988). Effects on quantity and quality of precipitation were monitored, and it seems that the annual precipitation has an increasing trend. Acidification of urban precipitation shows a more significant increasing trend.

## 3.5 Effects of forest

Effects of forest are investigated mainly by paired basins and plots. Contrary results were summarized on the effects on annual mean runoff R, e.g. it was found from loess plateau that R of a deforested basin is 1.7 to 3.0 times the R of a forested basin. However, in a humid region, R of a deforested basin is only 0,75 to 0,31 times R of a forested basin. For individual rainfall events on a forested basin time to peak is 2 to 4 times that of the bare one and the peak flow is only 1/5 to 1/10. Effects on annual mean erosion is rather definite, e.g. between 1964 to 1967 it was about 145 ton/km$^2$ in the forested basin and 733 ton/km$^2$ in the bare basin (Huanglongshan Basin). It was surprised that in 1962 annual precipitation on forested Wangjiahei Basin and deforested Dangjiahei Basin was about 598 mm and 504 mm respectively and annual runoff was about the same, i.e. 1.1 mm difference. However, the erosion was 0.7 ton/km$^2$ and 1 018 ton/km$^2$ respectively.
Another case study showed that the annual mean precipitation of forested Baojiagou basin was 647 mm and erosion did not occur. The bared Weiliagou basin however yield 1 594 ton/km$^2$ having annual mean precipitation less than that of the forested basin.

# 4 Comments on basin studies

## 4.1 Problematical concepts in basin studies

a) What is the prerequisites for an experimental basin?
Up to now it is firmly believed that in experimental/representative basins surface and subsurface boundaries should be closed. This led to find these basins mainly from upper reaches and, mostly in mountainous or hilly regions. It implies that it is near impossible to find an experimental basin in plain regions having a lot of hydrologic problems which just could display the ability of basin studies. The first Blue Brook Basin of China was cancelled and moved to a hilly region because subsurface boundaries do not exist, while the surface boundaries may change with different flood events. The aftermath of this cancellation became obvious 30 years later when evaluating water resources. So, the prerequisites of an experimental basin should be: the representativeness of its natural and anthropogenic conditions and the typical existing hydrological problems.

b) What are comparable paired basins?
To select paired basins, most attention was paid to the similarity of drainage area, shape and gradient of basin. It was found that it sometimes led to specious results. For example in a study of paired forested basins it was difficult to identify, wether the impact on runoff is due to the role of forest or to the role of soil layer, as the difference in forest cover may be related to inherent conditions of the basin, e.g. the condition of soil layer, or the direction of the basin, etc. In fact it is very difficult to make a complete survey for paired basins unless a hydrologic calibration is made for measurements during several years before the change in one of them occured. Otherwise, it is rather to make comparison within different years for single basins.

c) What are the representative sites for runoff factor measurements?
It was emphasized that for an experimental basin, networks of discharge, precipitation, soil moisture, etc. stations within the basin are necessary. Certainly it is indisputable. However, the stations involved in a network are mostly located by the method of uniform distribution. In the meantime, it is clear that runoff

parameters have its own related distance within a catchment, and sometimes it is distributed in a more complex manner. So, the representative sites should be that sites, least in number, which could fit a certain range of error allowed and depending on the scientific demand of the study, and under a certain confidence interval according to its distribution features within the basin.

## 4.2 Inadequacies of natural basins and the suggested experimental hydrological system

Some hydrological mechanism studies are to complex to study in basins, even in very small ones. Only empirical results can be obtained, i.e. the results can only be treated statistically or by correlation. Very unlikely we can turn a black box into brightness by this way.
In the experimental system suggested by Gu (1981) a circular concept is considered, as in Figure 1, from the natural "synthesis" condition to a condition of controlled parameters and then isolation of a process for lysimeters or laboratory experiments. Next again to a control condition in a more complex manner and subsequent testing to the natural condition and further research on a large scale. Here, "isolation" means to take a piece out of the complex hydrological process; "synthesis" means to combine several natural hydrologic processes together for research.

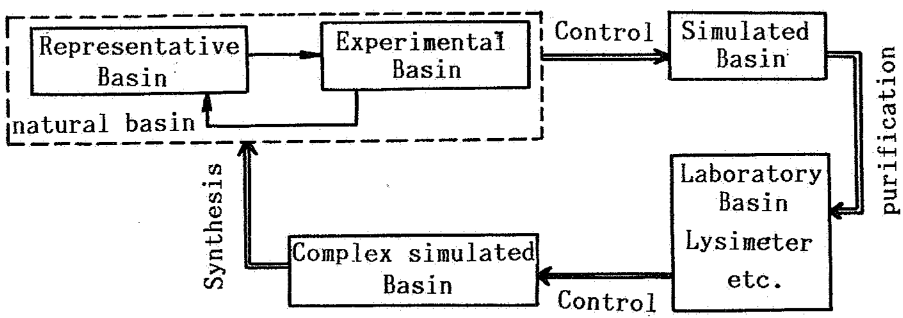


Figure 1. A concept of the experimental hydrological system

As a first try, an artificial experimental catchment serving as the simulated basin in Figure 1, was constructed. The drainage area is 490

$m^2$ and the surface gradient 10°-14°, with a concrete aquiclude of two inclined slopes and surrounded by an impermeable wall. Nearly homogeneous soil was selected to fill in. After three years since filling a special drainage trench system having four levels to collect different runoff components were designed and an intensive instrumentation was introduced (Figure 2).

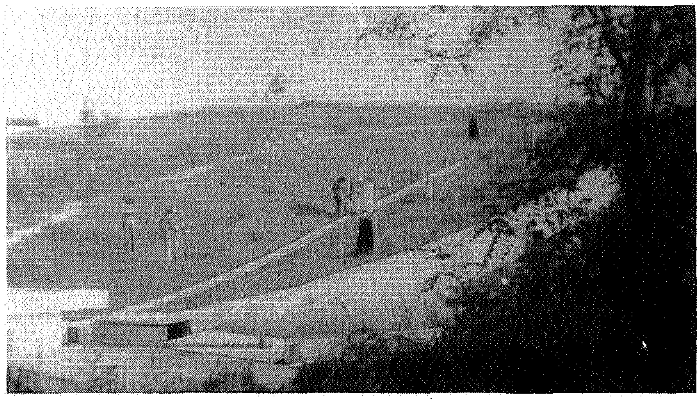

Figure 2. An artificial experimental catchment, Hydrohill (Gu, 1982)

It is hoped that the suggestion of this system could be an approach to solve the problem of extrapolation of results from experimental basins to large basins, one of the long standing criticism.

4.3 The shortcomings of current computation methods and the suggested "hybrid" hydrological basin research method

At present, the science of hydrology has to enhance its physical base and has to face with the complex hydrologic environment and problems. The hydrologic black box becomes more abyrinthian by modern complex human impacts. Our decades of practice experienced that simple arithmetical means are not adequate to meet the objectives of studies. It is considered to combine different methods together, i.e. to develop approaches using physical, chemical, isotopical, biogeochemical and hydrometeorological methods for basin studies, as a "hybrid" basin research. It became a proposed co-operative project on water pathways, biogeochemical processes and streamflow generation with USGS.

## Acknowledgements

The author is grateful to Prof. Dr. Mebus A Geyh for his valuable comments when he visited Hydrohill in 1988 and for his precious help. Sincere thanks are due to Dr. Roberto Gonfiantini and Dr. Yucel Yurtsever, IAEA, for their precious help. The author would like to give his sincere thanks to the scientific committee of this conference and Dr. Piet M.M. Warmerdam for their encouragement.

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# BIOGEOCHEMICAL CYCLES AND TRANSPORT OF CONTAMINANTS IN GROUNDWATER

# ISOTOPIC AND CHEMICAL HYDROGRAPH SEPARATION FOR A FORESTED HEADWATER MEDITERRANEAN STREAM FLOOD. A CRITICAL VIEW.

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Abstract

An isotopic ($^{18}O$) and chemical hydrograph separation is made for a storm event in a small upland mediterranean watershed (Cannone, Solenzara, Corsica, France). In that relatively simple case, discussion is focused on: - the comparison between the two methods and their limits,

- the role of throughfall in altering the incident rain chemistry,
- the origins of pre-event water.

Isotopic separation of the hydrograph shows that pre-event water represents 80 % of the storm runoff. The greatest uncertainty comes from the variation of the rain oxygen 18 value during the event. Chemical separation is much more difficult as three waters with different chemistry are likely to mix and the composition of rain is not a conservative parameter. Chemical separation with two components (pre-event stream water and rain water) as usually made are here either questionable (i.e. $HCO_3$, conductivity) or impossible (K, $SO_4$, Cl). The confrontation with the isotopic separation displays the error made in using bicarbonate and electric conductivity decompositions. Only the separation made with $SiO_2$ seems to be satisfactory .

Throughfall is of particular importance in altering the composition of incident rainfall and must be taken into account for chemical hydrograph separation in forested catchment.

Cl and $SO_4$ pattern in storm runoff implies the participation of soil water.

## 1 Introduction

Environmental questions concerning water quality such as transfer of pollutants, ecosystem acidification call for a new insight on water pathways and residence time of water within the different subsurface reservoirs. Hydrograph separation can be used for that purpose (Bottomley et al. 1984, Blowes and Gillham 1988, Dewalle et al. 1988). Here are reported the results of hydrograph separation for a storm event in Cannone basin which is a small forested mountainous catchment instrumented since 1981, as a part of the Solenzara Experimental Basin (Corsica - France). Attention is focused here on :

- the comparison between the isotopic and chemical methods of hydrograph separation, and their limits,
- the role of throughfall in altering the composition of incident rain water,
- the presence of soil water in storm runoff.

## 2 Site and methods

### 2.1 The Cannone watershed

Cannone is a permanent headwater stream of the Solenzara Basin (South East of Corsica, France). The characteristics of its drainage basin are the following : 0.33 $km^2$, elevation between 1020 and 1305 m, granitic substrate with a discontinuous weathered zone, forested (Pinus nigra ssp laricio), soils from rankers to ochre-podzolic soils (0.1 to 0.8 m). At low-level discharge, streamwater is provided by a fissure and arena aquifer.

### 2.2 Sampling, chemical and isotopic analysis

They are reported in a previous publication (Loÿe-Pilot and Jusserand, 1990).

## 3 The storm event of the 26$^{th}$ october 1981

**This storm is the first important event after the summer dry season. A few rain events during the october month have moistened the upper,**

organic layers of the soils.
The total rainfall is of 56,8 mm ; the hyetograph and the hydrograph are shown on figure 1. The total streamflow during the storm represents less than 3 % of the rainfall. No surface runoff was observed during the storm.

## 4. Hydrograph separation

### 4.1 Isotopic ( $^{18}O$) separation

Results are expressed in $\delta^{18}O$. Oxygene 18 content of rain (2 successive samples), stream water (hourly basis), soil water (before and after the storm), spring water (before and during the storm) was determined and is shown figure 1.
We were in an appropriate situation where the event water (rain) isotopic signal is different from that of pre-event water (soil + groundwater).The variation of stream water $\delta^{18}O$ shows the participation of rain water to storm runoff. Soon at the base of the rising limb of the hydrograph appears a little $^{18}O$ peak (point A, figure 1) wich can be interpreted as soil water flushed out from the lower part of the basin. The maximum of streamwater $\delta^{18}O$ variation occurs about one hour after the second peak (point B, figure 1) ; this result could mean that the rain water maximum contribution occurs one hour after the discharge peak, but it could also correspond to the arrival into the stream of the last, more negative rain fraction. This uncertainty cannot be solved on the basis of $^{18}O$ data only.
The similarity of soil water and groundwater $^{18}O$ signal allows an hydrograph separation with two storm runoff components : the pre-event event (o = old) water and the event (n = new) water :
$Qs = Qo + Qn$ and $Q.Cs = Qo.Co + Qn.Cn$
where Q = discharge, C = $\delta^{18}O$ , s = stream water
In this storm event the rain $\delta^{18}O$ is variable from - 13,7 to - 19,9 ‰ and hydrograph separation is realised according to two rain values : (i) the weighted average for the 2 successive rain fractions analysed and (ii) the estimated value for the weighted average of the 3 rain fractions. The separation was also done with 2 different values of old water : (i) soil water (- 7,71 ‰) and (ii) stream water (- 8, 10 ‰), a value very close to the spring waters before the event (- 7,98 / - 8,17 ‰). The maximum and minimum old water contribution in these 4

separations are represented on figure 1.

As found by many authors pre-event water is dominant in the storm runoff, varying from ~85 % at the first peak to ~ 65 % at the second peak.The greatest incertainty comes from the variation of the isotopic composition of the rain during the storm.

As regards to the origin of pre-event water, isotopic data do not allow in our case, to check the presence of soil water in storm runoff since soil water and groundwater have quite the same isotopic composition. Looking at the variation of the major dissolved elements give additional informations.

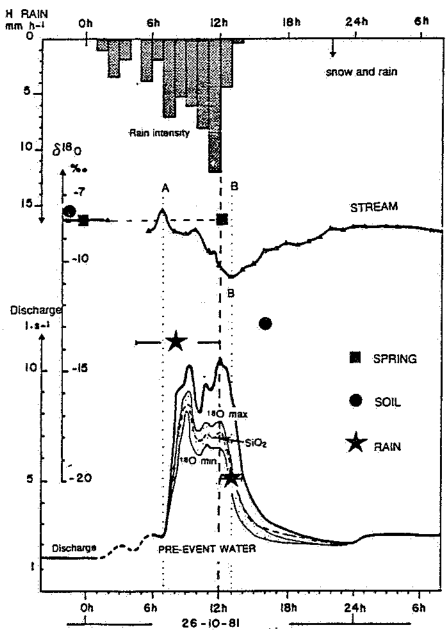


Figure 1. 1981 October storm. Isotopic composition of rain, soil, spring and stream waters before and during the storm. Isotopic hydrograph separation. Comparison with $SiO_2$ separation.

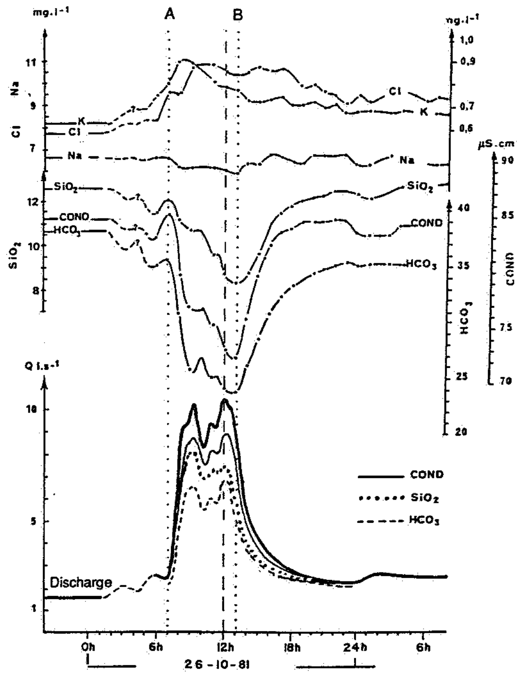


Figure 2. Concentrations of major ions in the streamflow during the storm. Tentative two-component chemical hydrograph separations.

## 4.2 Chemical variation of stream water and chemical hydrograph separation

### 4.2.1 Chemical variation of stream water

Also for the major dissolved elements, rain water ( pH = 4.7, dissolved load = 2.8 mg $l^{-1}$ ) is well different from stream water (pH = 7.6, dissolved load = 81 mg.$l^{-1}$). There are two types of dissolved inorganic elements (figure 2) : the first type including $SiO_2$, $HCO_3$, Na, Ca, Mg, follows the electric conductivity decreasing with increasing discharge and displays the dilution of old water by new water; the second type with Cl, $SO_4$, K, increasing with increasing discharge indicates that there is (an) other source(s) of solutes than rain and groundwater.

### 4.2.2 Hydrograph separation

A two-component hydrograph separation is impossible; however we tempted a classical two-component hydrograph separation to check how wrong we are with this simplistic hypothesis which neglects (i) the variation of rain chemistry during the event and (ii) the soil water component, the composition of which was unfortunately not analyzed.
The hydrograph separation was tried with, as usually done, pre-event water represented by stream water before the storm and event water being rain water- here the sampled fraction (4 h / 12 h) which triggers the storm-.
- Electric conductivity separation shows marked discrepancies with the isotopic separation, overestimating the contribution of old water,especially after the first discharge peak (figure 2). However conductivity is not specifically a good parameter as it integrates opposite variations of the different ionic species.
- Bicarbonates ($HCO_3$) are often used. They could be a good candidate for chemical hydrograph separation as they are effectively neither present in the rain , nor in soil water, soils pH being below 4.5. They could have given the contribution of groundwater. But they are not conservative and do not follow a simple mixing law but the action mass law , reacting with $H^+$ :- $(H^+).(HCO_3^-)/H_2CO_3 = K$ -. So they cannot be used in a mass balance. The classical two-component hydrograph separation (figure 2) underestimates the contribution of old water.
- $SiO_2$ separation. There is no $SiO_2$ in rain so there is no problem with

its variation during the storm. The two-component separation with the stream $SiO_2$ content (12,6 mg.$l^{-1}$) as old water value give a result quite similar to the isotopic separation (figure 1). $SiO_2$ separation confirms that the maximum dilution peak occurs one hour after the discharge peak (point B, figure 2). The similarity between the isotopic ans $SiO_2$ separations, already found by Hooper and Shoemaker (1986), is important as $SiO_2$ could be an useful, simple and inexpensive tracer for hydrograph separation. Its validity is nevertheless to be tested in other cases and does not allow to distinguish the respective contributions of soil water and groundwater.

Other diluted elements during the storm elements such as Na, Ca, Mg could be used, but their relative variation during the event is much less than for the $SiO_2$, $HCO_3$ or electric conductivity.

The increase of elements such as Cl, $SO_4$, K during the storm demonstrates that a two-component mass balance is invalid and implies other solute sources than those investigated (groundwater and rain). Two other sources are likely : soils and throughfall.

## 5 The role of throughfall

In such a forested catchment rain water crosses the canopies before reaching the soil surface.

Table 1. Modification of rain chemical composition by throughfall: data for the 3-10 / 9-11 period and estimated values for the October 26 rain.

| | | Cl | SO4 | HCO3 | Na | K | Ca | Mg | SiO2 | H | pH | Cond. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | µeq/l | | µS/cm |
| **RAIN** | 3-10/9-11-81 | 4.2 | 2.6 | 0 | 1.96 | 0.11 | 0.54 | 0.20 | 0 | 59 | 4.23 | 36 |
| **THROUGHFALL** | 3-10/9-11-81 | 19.4 | 9.7 | 0 | 11.3 | 1.70 | 3.22 | 1.26 | 0 | 37 | 4.43 | 97 |
| **CONCENTRATION RATIO** | | 4.6 | 3.7 | | 5.7 | 15.4 | 5.9 | 6.3 | | 0.6 | | 2.7 |
| **THROUGHFALL** | 1h30/4h | 14.2 | 7.0 | 0 | 5.9 | 6.2 | 4.2 | 0.75 | 0 | 28 | 4.55 | 94 |
| | 4h/12h | 2.6 | 4.4 | 0 | 1.6 | 1.4 | 1.5 | 0.13 | 0 | 10 | 5.00 | 27 |
| **estimated value** | 12h/13h30 | 0.5 | 1.8 | | 0.3 | 0.15 | 0.8 | 0.06 | 0 | 6 | 5.22 | 11 |
| **for 26-10-81** | 1h30/13h30 | 3.7 | 4.5 | 0 | 1.9 | 1.8 | 1.8 | 0.19 | 0 | 11 | 4.94 | 33 |

The modification of rain chemistry by throughfall is not taken into account in hydrograph separation except in recent works( Dewalle et al. 1988). Table 1 shows the modification of rainwater by throughfall for a period of one month (3-10/9-11 1981) around the studied event. Enrichment ratios are from 4 to 15, potassium being the most enriched. $SiO_2$ still absent of throughfall waters is therefore an appropriate element for chemical hydrograph separation.

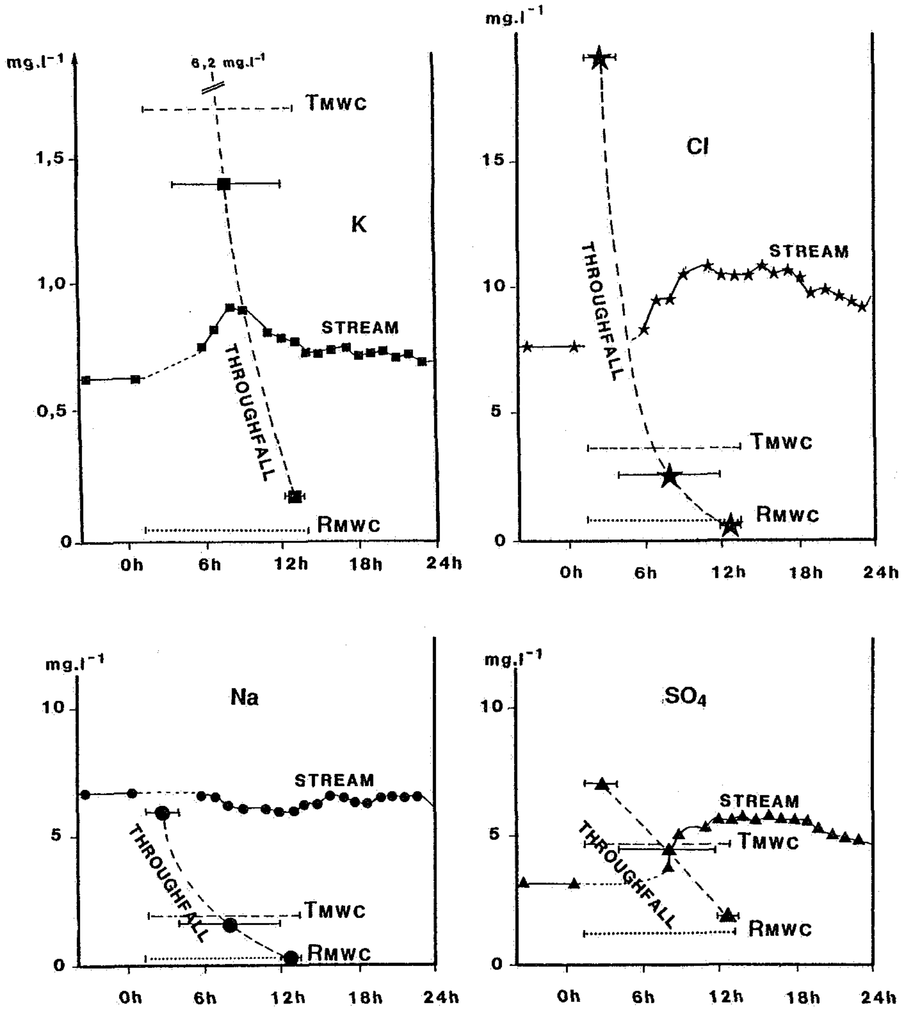


Figure 3. Comparison of K, Na, Cl, $SO_4$ concentrations in streamwater with their estimated values in throughfall. **Tmwc**: throughfall mean weighted concentration, **Rmwc**: rain mean weighted concentration.

Throughfall chemistry could not be studied during the 26 october event and we applied the October average enrichment factor to the 26 october rain event(table 1). Figure 3 displays the variation of stream water and the estimated throughfall water concentrations during the storm. The mean weighted value of potassium in throughfall water would be much higher than the river and spring values and potassium in the stream water follows fairly well the postulated behaviour of throughfall potassium; its pattern might be explained essentially by the arrival of throughfall waters in the stream.

For sodium, the throughfall waters are always lower than streamwater, so that they dilute the pre-event water. However an hydrograph separation with Na, Ca or Mg should use throughfall concentrations,not rain ones.

The chloride estimated mean weighted concentration of throughfall water is well lower than pre-event stream water's one and cannot explain the increase of chloride and its high level during the storm. The chloride throughfall pattern, with a relative high value for the first part of the rain event, may explain the early part of the rising limb of the chloride chemograph,but not the chloride increase at and after the discharge peaks. So an extra source of chloride is to be found

The sulfate behaviour is intermediate between potassium's and chloride's one. A great part of the sulfate variation in the stream could be explained by throughfall, especially until the second discharge peak. But the sustained high level of $SO_4$ with decreasing discharge must also be explained by an other solute source.

Throughfall influence on stream water chemistry helps to understand the behaviour of non-diluted elements and explains completely the variations of potassium in stream water; but for sulfate and especially for chloride, other source(s) of solutes must be looked for.

## 6 Occurence of soil water in storm runoff

The role of soil water in storm runoff generation is still a matter of debate; this problem is reviewed in Löye-Pilot and Jusserand 1990.

Before the storm the only preexistent waters in the catchment are :(i)- groundwater (fissure and weathered profile aquifer) the chemistry of which did not change during the storm, and (ii)- soil water (from the upper, organic soil layers and from the whole profile in variable source area). The water stored in soils is well greater than the volume of the storm (Loÿe-Pilot et Jusserand 1990) and could contribute significantly to the storm runoff.

However, the arrival of soil solutes into the stream water do not imply the arrival of soil water. In fact solutes adsorbed on the soil colloidal absorbing complex are not already dissolved in water; such solutes, picked up by rain in dry soil layers and arriving in stream, do not correspond to preexistent soil water. But in moistened layers, solutes are picked up by rain water which mixes with and dilutes preexistent water; in that case solutes come to the stream with soil water.

Additionnal sources needed to explain chloride and sulfate behaviour could be found in soils and at least a part of these solutes comes from preexistent soil water. As we did not perform soil water analysis we cannot calculate its contribution.

## 7 Conclusion

Isotopic separation is a very useful tool to trace water movements in a catchment and to determine the sources of storm runoff water. But all water sources must be checked to get a non biased hydrograph separation. Especially soil water(s) must be measured. In the studied case, variation of rain water isotopic signal during the event is the main source of error.

For the studied event, streamwater electric conductivity, $SiO_2$, $HCO_3$, Na, Mg, Ca, patterns show the dilution of pre-event water by rainwater; but K, Cl, $SO_4$ increasing in streamwater during the storm, point out the occurence of other sources of solutes than only groundwater and rain. Throughfall modification of incident rain chemistry explains the potassium and partly the chloride and sulfate behaviour. Solutes from soils (pre-existent water and absorbing complex) are needed to fully account for streamwater chloride and sulfate. Chemical hydrograph separation is impossible in our case, the soil water component having not been measured. However the comparison of the classical two-components separation with $^{18}O$ separation displays the error introduced by such a simplistic approach. $HCO_3$ intrinsically cannot be used for hydrograph separation and electric conductivity is to be used with wariness: $SiO_2$ separation is very similar to isotope separation; usually neither present in rain nor throughfall $SiO_2$ might be a good tool for chemical hydrograph separation but its validity must be further studied.

The examination of stream water chemistry variation helps to avoid oversimplificating hypothesis, but all elements must be checked, not the only ones fitting with the original assumptions.

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# TRANSPORT AND TRANSFORMATION OF INORGANIC FORMS OF NITROGEN THROUGH HORNBEAM CANOPY INTO A SURFACE STREAM

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Abstract

The quality of rainwater that penetrates through the canopy and infiltrates into the soil layers of the watershed is influenced by many processes. The results of the measurements of concentrations $NH^+_4$, $NO^-_2$, $NO^-_3$, $CL^-$, pH and electrical conductivity of rainwater influenced by the vegetation and the soil of the watershed are presented. It was being found that the water quality parameters have changed not only by penetrating through the subsystems of the watershed (interception, stemflow, organic and humus layer of the soil, the whole geological layer) but are changing during the seasonal periods, as well. These results are the basis for a more detailed measurement program for the evaluation of the influence of forest on runoff and its quality.

## 1 Introduction

In recent time research of many authors has shown that rainwater is effected by a number of different parts of the environment with many physical, chemical and biochemical processes. Burt (1979), Moldan and Paces (1980), Bedrna (1981), and Klimo (1982) have studied the influence of acid atmospheric deposition on soil acidification with special emphasis on the quality of infiltrating water and surface water, respectively. In our case the research program has been set up on the basis of these studies and carried out in the central part of Slovakia at the experimental watershed Lesný. The effects of the subsystems interception, stemflow, organic and humus layer and the whole geological horizon on the rain water was studied. In the water samples from these subsystems the following parameters have been analyzed: $NH^{+}_{4}$, $NO^{-}_{2}$, $NO^{-}_{3}$, $Cl^{-}$, pH and electrical conductivity.

## 2 Site description and methods of data collection

### 2.1 Site description

This study was done at the experimental watershed Lesný (8,64 ha) situated in the highland Strazovská vrchovina, the Central part of Slovakia. Altitude ranges from the cross 350 - 400 m.a.s.l. According to the geological condition there are flysh series of strata, sandstones conglomerates and marls. The upper soil layer is organic and humus, the lower one consists of brown soil.

The forest consists of mixed hornbeam and pine-tree, of which 95% is hornbeam and 5% pine-tree. The age of the canopy is about 55 - 60 years. The climate of this watershed is characterized by precipitation, temperature and humidity parameters. The elements of the water balance of the period 1965 - 1985 amounts to: mean annual precipitation 720 mm, mean annual outflow 177,6 mm, mean annual evapotranspiration 551,7 mm. The mean monthly temperature ranges between -5,8°C and 20,3°C. Minimum was found in January and maximum in August. Hydrological problems, concerning runoff processes, evapotranspiration and interception have been investigated in this basin since 1962. In connection with this hydrological research program, the research of the effect of vegetation on the quality of rainwater had been started. The results of measurements from an interception plot in the period 1987 - 1988 are presented.

### 2.2 Methods of data collection

In the experimental watershed Lesný the water quality is measured of samples taken from:

- rainwater at the open area;
- throughfall;
- stemflow;
- rainwater, infiltrated through the organic and humus soil layer (ca. 15 cm);
- water of the stream, draining the watershed.

Samples of rainwater and of dry deposition on the open area are collected from three rain gauges. Similarly, sampling is performed in the case of throughfall, stemflow and of water from lysimeters. The interception plot is 10 by 10 m, where rain gauges and a collector for stemflow are installed. There are three open lysimeters installed in the watershed. The method for sampling as by Klimo (1982) is being used. Samples are taken daily during rainfall events. Clear 1 litre polyethylene bottles are used to store water samples. In the period between sampling and chemical analyses, samples are kept under temperatures between 2 and 5°C. Water quality parameters of these samples are analyzed according to the "Standardized analytical methods (1980)". With this sampling program meteorological and hydrological characteristics (precipitation, temperatures, humidity, discharges) are measured as well.

## 3 Influence of hornbeam canopy on the composition of rainwater

### 3.1 Changes pH values of throughfall

When the composition of rainwater penetrating through the canopy is investigated it is necessary to take into account human effects upon the canopy. This effect in the case of watershed Lesný is not very expressive. In the present situation the pH was in the range of 6,0 - 7,2 and it is known that a pH value 5,6 of rainwater may be taken as natural water. From this reason watershed Lesný is considered as a region with little human effect. The pH values of throughfall in hornbeam canopy were moderate increasing or remained on the same level. Increasing of the pH values may be explained by $Ca^{2+}$ cations on the leaves of trees (originated from deposition of the soil dust particles). The pH values of rainwater that has infiltrated and passed through the organic and humus soil layer are rapidly decreased by about a value of 0,2 - 1,1. This fact is caused by increasing concentrations of the organic acid and the compound of nitrogen. The geological bedrock of watershed Lesný neutralizes the moderate acid percolating water. The range of pH in spring water was found between 7,9 and 8,1. In Figure 1 results of measurements from the years 1987 - 1988 are shown. It has been found that geological bedrock had the main effect on the pH of rainwater.

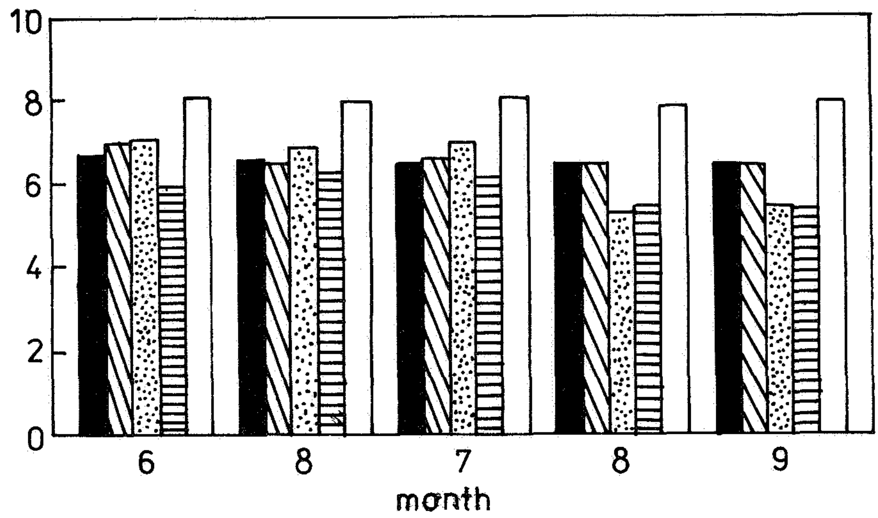


Figure 1. Transport Matter pH (average monthly values) Watershed Lesný, 1987/1988

3.2 Changes of inorganic nitrogen concentrations

In the research that is done in watershed Lesný, a lot of attention is paid to transport and transformation of $NH^{+}_{4}$, $NO^{-}_{2}$ and $NO^{-}_{3}$ through the hydrological system of the watershed. The ammonia concentrations of throughfall mostly decreased between range 0,05 - 3,0 $mg.l^{-1}$. In the case of stemflow an increase of $NH^{+}_{4}$ concentration in the range between 0,1 - 3,0 $mg.l^{-1}$ has been found mainly in the summer months. In the percolating water this component of nitrogen increases except for July. Because in principle ammonia is transformed to nitric acid by nitrifying bacteria in the soil and deeper horizons, the ammonia concentrations in the surface water of stream Lesný was found negligible. In Figure 2 average monthly values of ammonia concentrations are given. The changes of nitrite concentrations of the penetrating rainwater was found insignificant. But their values are important to know the transforming reactions (nitrification).

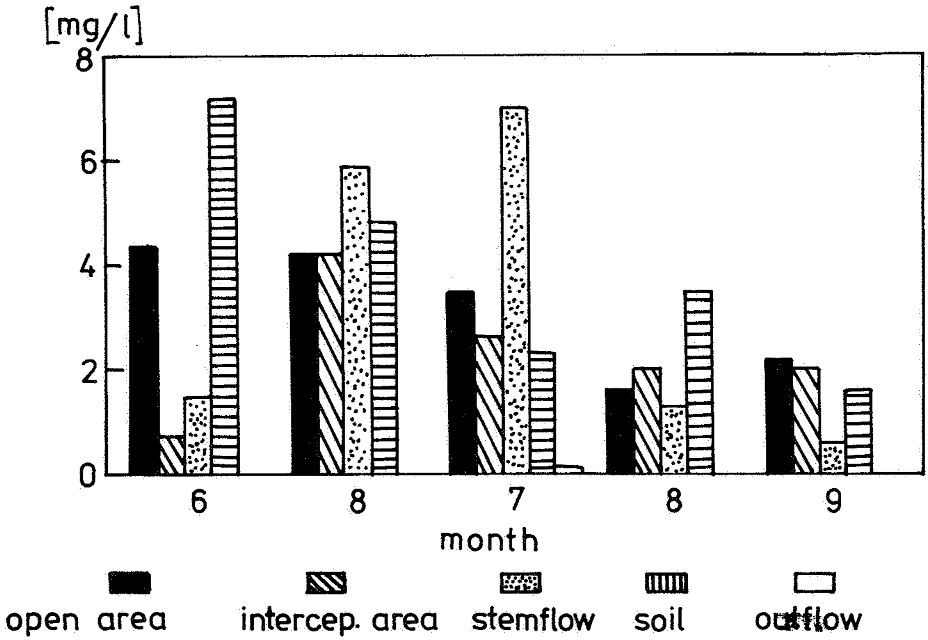


Figure 2. Transport Matter-Ammonia (monthly values) Watershed Lesný, 1987/1988

While ammonia and nitrite concentrations of the penetrating rainwater through the system of watershed Lesný was rapidly decreased, nitrate moves through the whole system and occurred in the surface water of the stream.

The effect of concentration and dilution on nitrate concentrations in the case of throughfall was measured. Research of Van Breemen et al. showed the similar results. In fact the deposition of nitrates in woodlands is much higher than in the open field, because dry deposition is quite high here. Nitrate concentrations of stemflow have increased, but these higher concentrations have only local meaning around the woods.

In the organic and humus zone the $NO^-_3$ concentrations in the percolating water have increased. Maximum value was 41,0 $mg.l^{-1}$ $NO^-_3$. Fortunately, flow of rainwater to the deeper soil horizons decreased the nitrate concentrations. This decrease could be explained by various neutralizing processes in soil, microbial processes (e.g. denitrification) and extraction by plant roots. Klimo (1982) has shown similar results for spruce ecosystem. These data indicate that the system of woodland has ability of self-control of nitrate output concentration, as also shown by Kovda (1975).

## 3.3 Changes of chloride concentrations and electrical conductivity

Assuming conservative nature of chloride their values could be changed in the system of watershed Lesný only by washing out (leaf area, soil), weathering of minerals, extraction by plant roots. The highest chloride concentrations were found in the lysimeter water. The range was 3,5 - 18,0 $mg.l^{-1}$.

Table 1. Distribution of some water quality parameters of rainwater on 23 August 1988

| parameter [$mg.l^{-1}$] | open field | inter.plot | stemflow | soil | outflow |
|---|---|---|---|---|---|
| $NH^+_4$ | 1,6 | 2,0 | 1,7 | 6,3 | 0,0 |
| $NO^-_2$ | 0,1 | 0,1 | 0,09 | 0,5 | 0,0 |
| $NO^-_3$ | 1,9 | 2,5 | 2,0 | 16,0 | 2,5 |
| $Cl^-$ | 2,5 | 3,5 | 2,5 | 7,0 | 8,0 |
| elec. cond. 1) | 46,5 | 50,0 | 80,0 | 170,0 | 360,0 |
| pH | 6,8 | 6,5 | 6,4 | 5,5 | 7,8 |

1) [$\mu s.cm^{-1}$]

In the root zone the concentrations in the percolating water have increased and stabilized with depth. In our case the chloride concentration of spring water was 9,0 ± 1,0 $mg.l^{-1}$. For this fact evapotranspiration is responsible. The average annual precipita- tation in the watershed Lesný amounts to 720 mm, of which about 550 mm evaporates. This results in a net infiltration and percolation to the groundwater of 170 mm. The ratio between $Cl^-$ concentration of precipitation and spring water was 2 - 2,5. Williamson et al. (1987) have found a ratio between 9 and 15.

The electrical conductivity shows similar tendency as the chloride concentration. Their values of spring water are approximately 9 times higher than of rain water (400,0 $\mu s.cm^{-1}$). In Table 1 measurements of rainfall event on 23 August 1988 are presented.

## 4 Conclusions

The results based on data concerning the atmospheric deposition of nitrogen and the infiltration of rainwater in relation with type of vegetation may be presented as follows:

- hornbeam canopy in the watershed has a significant effect on transport of inorganic nitrogen forms;
- the system of watershed Lesný has ability of self-control of nitrate response;
- the seasonal concentration variations of the inorganic nitrogen forms are related with temperature and precipitation conditions of watershed.

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# STUDIES OF ELEMENT BUDGETS IN THE BLACK FOREST (GERMANY) ON EXPERIMENTAL WATERSHEDS WITH DIFFERENT TREATMENTS

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## Abstract

Effects of forest fertilization and atmospheric deposition on the element cycling of two typical spruce ecosystems in the Black Forest are studied. Interrelations between the terrestrial and aquatic system are assessed using an integrated approach which combines flux measurements in representative plots with budgets of small experimental watersheds. The paper describes approach, treatments, field installations, methods, and site conditions. Treatments comprise whole-watershed application of readily soluble fertilizers such as $(K,Mg)SO_4$ to improve the nutritional status of the stands as well as $(NH_4)_2SO_4$ to simulate excess atmospheric deposition. Water and element budgets are presented for the periods prior and subsequent to treatments.

## 1 Introduction

The elements nitrogen and sulfur play a key role in the acidification of soil and water because the mobility of the anions $NO_3^-$ and $SO_4^{2-}$ controls cation export (Reuss and Johnson, 1986). Sulfur is the element which is normally most important for the acidity in wet and dry deposition. A more practical reason to study sulfur cycling in forest ecosystems evolves from the application of readily soluble fertilizers, such as $(K,Mg)SO_4$ in order to revitalize declining stands suffering from severe Mg (and/or K) deficiency. Even though salt fertilization has been demonstrated to be an efficient tool to improve Mg/K-nutrition and vitality of forest stand (Hüttl, 1989), only limited knowledge of the pedo- and hydrochemical effects associated with the introduction of the anion sulfate exists. Recently, discussion has centered on the impact of increasing atmospheric nitrogen inputs, mainly originating from agricultural sources. Elevated nitrogen levels in soil solution may contribute to acidification and lead to nutritional disturbances (imbalances, deficiencies) and impaired nutrient uptake due to a reduction in mycorrhizal growth (Skeffington and Wilson, 1988). Furthermore, an excess nitrate leaching from the root zone may jeopardize the use of groundwater and surface water for drinking water when $NO_3^-$ and Al concentrations exceed threshold values.

## 2 Approach

In the research project ARINUS (acronym of the German project title), the effects of restabilization measures (fertilization with readily soluble Mg/K sulfate fertilizers) and atmospheric deposition on the element cycling of typical spruce ecosystems in the Black Forest are studied. The objective is to separate and quantify the internal and external sources of the elements N and S and their cycling in forested watersheds (Zöttl et al., 1987; Feger et al., 1988). Due to unfavorable soil and bedrock conditions, a major part of the Black Forest is highly susceptible to soil and water acidification. Research initiated in 1986 will continue until the mid 1990's as part of the CEC project ENCORE (European Network of Catchments Organized for Research on Ecosystems). ARINUS integrates ecological studies on the watershed and the plot levels.

Experimental watersheds can be ideal basic units for studying biogeochemical fluxes. Estimation of water and element input-output budgets for a watershed provides information about the response of the system as a whole to external influences such as changing atmospheric inputs or management practices (biomass harvesting, fertilization). A watershed approach is inherently necessary to quantify the effects of pertubations on the hydrosphere, since the watershed is the ultimate hydrologic unit and, moreover, the smallest complete unit of a landscape that encompasses linked aquatic and terrestrial systems. With a pure watershed input-output approach it is difficult, however, to identify and quantify biogeochemical processes occuring within the system. Information on the internal processes can only be derived from the study of element cycling of 'representative' plots (ecosystems) within the watershed. Fig. 1 gives a schematic illustration of the different system levels and the compartments between which water and element fluxes are measured in the ARINUS project.

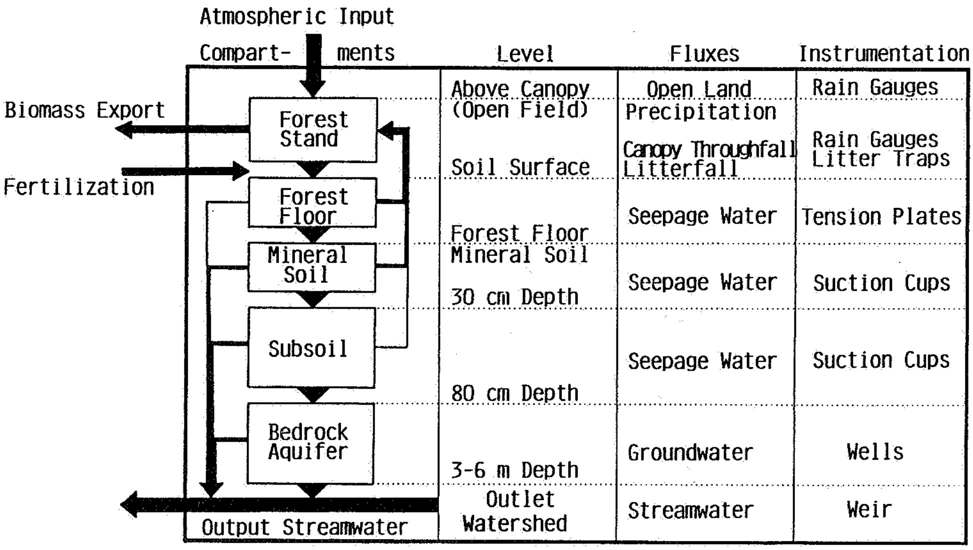


Figure 1. Element and water fluxes in a watershed with compartments and instrumental design.

With a watershed-scale experimental application of N and S fertilizers, several hypotheses can be tested under defined conditions. Through the addition of $(NH_4)_2SO_4$, an excess input of both acidity and nitrogen is achieved. Soils will be acidified to the extent $NO_3^-$ is leached with a base cation. Furthermore, this treatment may enhance N/Mg imbalance in the nutrition of the stand. A short-term decrease in soil solution pH and Al mobilization are likely to occur when unbuffered fertilizer salts such as $MgSO_4$ are applied to acidic soils. Elevated Al concentrations may damage the fine roots and/or impair nutrient uptake. Both treatments may acidify groundwater and streamwater to the extent that $NO_3^-$ and/or $SO_4^{2-}$ will be leached with $H^+$ and $Al^{n+}$.

## 3 Study Areas

Research is conducted in two experimental watershed areas, Schluchsee (47°49'N, 8°6'E) and Villingen (48°3'N, 8°22'E). Both areas are located in the higher altitudes of the Black Forest (SW Federal Republic of Germany). Each study area consists of several small experimental watersheds located ajacent to each other. All watersheds are completely forested and not affected by agricultural activities, uncontrolled fertilization or road salts (for a detailed site description see Zöttl et al. (1987) and Feger et al. (1990)).

At Schluchsee (5° C mean annual temperature, 1900 mm precipitation) well-drained podzols and podzolized brown soils are the most common soil types. Bedrock consists of the coarsely weathering "Bärhalde" granite which is extremely poor in Ca and Mg. The size of the 3 adjacent watersheds varies between 7 and 11 ha. Elevation ranges between 1145 and 1253 m a.s.l.. The individual watersheds have well-defined boundaries and are drained by perennial first-order streams. The whole area is uniformly covered with managed plantations of 40 to 60 year-old Norway spruce (*Picea abies* (L.) Karst.). Since the late 1970's a large-scale yellowing of the older needles has been observed in spruce of this area. The yellowing symptoms, which result directly from Mg deficiency, are widespread in many high-altitude sites in Central Europe (cf. Rehfuess, 1987; Roberts et al., 1988). Ground vegetation consists of blueberry (*Vaccinium myrtillus* L.), *Luzula sylvatica* (L.) Gaud., and *Blechnum spicant* (L.) Roth. The original forest association, dominated by beech (*Fagus sylvatica* L.), was replaced by spruce plantations about 200 years ago. Due to high hydraulic conductivity throughout the entire soil profile (loamy sands with a high content of fine gravel), vertical water flow is predominant.

The size of the Villingen watersheds (870-954 m a.s.l.) ranges between 38 and 46 ha. Forest consists mainly of 80 to 100 year-old spruce mixed with silver fir (*Abies alba* Mill.) and Scots pine (*Pinus* *silvestris* L.). Mean annual precipitation of roughly 1200 mm is lower than at Schluchsee. The annual temperature averages 6° C. The bedrock consists of Mesozoic quartz-rich sandstone layers ("Buntsandstein"). Deep seepage seems not to be important, since the sandstone is underlain by granite, which forms the confining bed. The soils are dominated by sandy-loamy acid brown soils ("Sauerbraunerden", dystric cambisols) and stagnogleys. Stagnogleys (stagnopodzols) with *Sphagnum* moss are common at lower slope positions. The upper mineral horizons are characterized by a sandy texture, whereas the subsoils by a higher clay content. Former forest management practices, such as litter removal and forest grazing, have substantially added to the unsuitable chemical soil properties. This is reflected in a weak nutrition of the stands with respect to N, P, and K. Higher clay contents together with elevated bulk densities in the sub soil of both soil types cause a decrease in coarse pore volume and hydraulic conductivity resulting in widespread waterlogging. While stagnant moisture occurs only periodically in the brown soils, the stagnogleys normally show permanent waterlogging. Due to these soil hydraulic conditions, shallow lateral drainage dominates during storm runoff periods.

## 4 Treatments

After one year of pre-treatment measurements, entire watersheds were treated with solid fertilizers in June, 1988. Applications were done manually. S1 and V1 remained untreated, thus serving as controls. S2 was treated with 750 kg $ha^{-1}$ $MgSO_4$ and V2 with 850 kg $ha^{-1}$ $(K,Mg)SO_4$ to counteract the acute deficiency of the stand with Mg and K, respectively. 700 kg $ha^{-1}$ $(NH_4)_2SO_4$ was applied in S3 and V3 in order to simulate excess atmospheric deposition. The applied amounts of sulfur (170 kg $ha^{-1}$) and nitrogen (150 kg $ha^{-1}$) correspond to 10 to 15 times the present annual deposition of both elements at these sites. In addition, $(NH_4)_2SO_4$ has a considerable acidification potential depending upon N transformations in the soil. All 4 treated watersheds received 170 kg $ha^{-1}$ S which enables the direct comparison of the treatments. A small amount of NaCl (50 kg $ha^{-1}$) was mixed in both fertilizers. With chloride as a tracer, water and fertilizer transport can be followed and, moreover, the accuracy of water and element budgets be ascertained. In autumn of 1990, watershed S4 will be limed with 4000 kg $ha^{-1}$ of dolomitic limestone. In this experiment, the changes in acidity and the kinetics of Mg dissolution will be studied.

## 5 Methods

Fig. 1 presents schematically the instrumental design of each watershed. Estimates of atmospheric inputs are based on the analysis of samples from bulk collectors both in the open field and in the forest stands. In each watershed, discharge is permanently recorded at 60° Thomson weirs. Samples are collected weekly. Sampling is more frequent during periods with high discharge. Hydrologic instrumental design and chemical methods are described in detail by Feger et al. (1990).

## 6 Preliminary Results

The water fluxes measured in all watersheds during the period June 1987 through May 1989 are given in Table 1.

Table 2 presents the element output from all watersheds for the one-year pre-treatment period. The element output rates of the individual watersheds prior to manipulations are highly comparable within each area. This allows for clear interpretation of effects induced by the treatments.

Tables 3 and 4 provide the element input rates via open land bulk precipitation of the control watersheds for the two-year study period. Precipitation at both sites is dilute and acidic. Despite the differences in the amounts of precipitation at both sites (Table 1), the deposition rates are very similar. The low chloride and sodium load is typical for continental areas. The proton input rates of 0.27 at Schluchsee and 0.22 kg $ha^{-1}$ $yr^{-1}$ at Villingen correspond to a mean weighted pH value of 4.8 for both areas. This coincides with the

Table 1. Water budgets of the ARINUS experimental watersheds at Schluchsee and Villingen for the period June, 1987 through May, 1989.

| Watershed | SCHLUCHSEE S1 | S2 | S3 | VILLINGEN V1 | V2 | V3 |
|---|---|---|---|---|---|---|
| Time Period | 1987/6/1 - 1988/5/31 | | | | | |
| Precipitation (mm) | 2301 | 2301 | 2301 | 1616 | 1535 | 1433 |
| Runoff (mm) | 1960 | 1968 | 1980 | 874 | 890 | 813 |
| Runoff/Precipitation | 0.85 | 0.86 | 0.86 | 0.54 | 0.58 | 0.57 |
| Evapotranspiration* | | 493 | | | 641 | |
| Time Period | 1988/6/1 - 1989/5/31 | | | | | |
| Precipitation (mm) | 1599 | 1599 | 1599 | 1047 | 998 | 956 |
| Runoff (mm) | 1104 | 1097 | 1170 | 353 | 309 | 297 |
| Runoff/Precipitation | 0.69 | 0.69 | 0.73 | 0.34 | 0.31 | 0.31 |
| Evapotranspiration* | | 531 | | | 697 | |
| | Annual Means (2-year Period) | | | | | |
| Precipitation (mm) | 1878 | 1878 | 1878 | 1332 | 1267 | 1195 |
| Runoff (mm) | 1532 | 1533 | 1575 | 614 | 600 | 555 |
| Runoff/Precipitation | 0.82 | 0.82 | 0.84 | 0.46 | 0.47 | 0.46 |
| Evapotranspiration* | | 512 | | | 669 | |

* Potential evapotranspiration (formula of Haude (1955) with correction factors according to Damann (1965) and Enders (1978))

Table 2. Element output (kg $ha^{-1}$ $yr^{-1}$) from the ARINUS experimental watersheds in the year prior to treatments (June 1987 through May 1988).

| | Output from Watersheds (kg $ha^{-1}$ $yr^{-1}$) S1 | S2 | S3 | V1 | V2 | V3 |
|---|---|---|---|---|---|---|
| $H^+$ | 0.09 | 0.10 | 0.07 | 0.23 | 0.03 | 0.06 |
| $Na^+$ | 26.6 | 25.9 | 24.5 | 6.3 | 5.8 | 5.7 |
| $K^+$ | 11.2 | 10.6 | 8.6 | 3.8 | 4.4 | 4.3 |
| $Ca^{2+}$ | 20.9 | 22.4 | 21.2 | 7.6 | 13.4 | 10.8 |
| $Mg^{2+}$ | 3.5 | 3.4 | 3.5 | 2.7 | 4.1 | 4.6 |
| $NH_4^+$-N | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| $NO_3^-$-N | 10.7 | 10.8 | 6.0 | 0.5 | 0.6 | 0.6 |
| N-tot* | 10.8 | 10.9 | 6.0 | 0.5 | 0.6 | 0.6 |
| $SO_4^{2-}$-S | 26.1 | 25.9 | 25.0 | 16.2 | 13.7 | 13.2 |
| $Cl^-$ | 12.8 | 11.9 | 10.9 | 8.3 | 8.6 | 8.6 |
| $HCO_3^-$ | 32.2 | 26.8 | 36.4 | 10.8 | 18.9 | 18.9 |
| Al | 7.10 | 5.79 | 4.57 | 5.72 | 2.94 | 2.98 |
| Mn | 0.53 | 0.59 | 0.36 | 1.17 | 0.79 | 0.55 |
| Fe | 0.13 | 0.25 | 0.23 | 0.61 | 0.60 | 0.45 |

* N-tot = $\Sigma NH_4^+$-N + $NO_3^-$-N

nitrogen and sulfur input, which is low to moderate as compared with other areas in Central Europe receiving similar amounts of precipitation. For many elements, the load in canopy throughfall differs distinctly from that in bulk precipitation. A comparison of the input and output fluxes in Tables 3 and 4 provide some of the more interesting insights into the system response.

Table 3. Mean annual element fluxes (kg $ha^{-1}$ $yr^{-1}$) in control watershed S1 for the period June 1987 through May 1989 and net changes in streamwater output from the treated watersheds for the year after application (1988/6/1 - 1989/5/31).

| | | | Streamwater Output | | |
|---|---|---|---|---|---|
| kg $ha^{-1}$ $yr^{-1}$ | Preci-pitation | Canopy Throughfall | S1 | Net Changes* S2 | S3 |
| $H^+$ | 0.27 | 0.30 | 0.06 | 0.05 | 0.12 |
| $a^+$ | 4.5 | 5.1 | 21.7 | 3.6 (18%) | 4.5 (23%) |
| $K^+$ | 1.9 | 11.6 | 8.7 | 0.9 | 2.2 |
| $CA^{2+}$ | 5.2 | 6.4 | 16.4 | 5.2 | 9.6 |
| $Mg^{2+}$ | 0.9 | 1.2 | 2.7 | 6.6 (6%) | 2.3 (2%) |
| $NH_4^+$-N | 6.3 | 4.0 | < 0.1 | < 0.1 | 1.8 |
| $NO_3^-$-N | 4.4 | 4.9 | 8.3 | 1.7 | 13.9 |
| N-tot** | 10.7 | 8.9 | 8.3 | 1.7 | 15.7 (10%) |
| $SO_4^{2-}$-S | 8.2 | 10.4 | 19.9 | 20.2 (12%) | 16.0 (9%) |
| $Cl^-$ | 7.1 | 9.0 | 9.9 | 6.6 (22%) | 8.0 (26%) |
| $HCO_3^-$ | 15.0 | 10.3 | 26.5 | -3.2 | -9.6 |
| Al | 0.09 | 0.20 | 4.87 | 3.10 | 7.35 |
| Mn | 0.05 | 0.35 | 0.38 | 0.27 | 0.44 |
| Fe | 0.08 | 0.12 | 0.10 | 0.03 | 0.02 |

* Percentage of losses of applied elements
** N-tot = $\Sigma$ $NH_4^+$-N + $NO_3^-$-N

Normally, input and output of chloride are expected to roughly balance over the long term, since this ion is assumed to behave conservatively and not to be affected by biogeochemical processes. Although the data represent only two years of measurements, the chloride budget is surprisingly well balanced. This confirms indirectly the assumption that other water fluxes which are not measurable (e.g., deep seepage) are insignificant. Furthermore, Tables 3 and 4 reveal the net changes in element output from the two fertilized watersheds for the first year after application. Net changes are related to control watersheds S1 and V1, respectively. From 30 kg,ha$^{-1}$ $Cl^-$ applied as a hydrological tracer, a portion of only 18 to 26% has left the fertilized watersheds within one year after treatment.

Table 4. Mean annual element fluxes (kg ha$^{-1}$ yr$^{-1}$) in control watershed V1 for the period June 1987 through May 1989 and net changes in streamwater output from the treated watersheds for the year after application (1988/6/1 - 1989/5/31).

| kg ha$^{-1}$ yr$^{-1}$ | Precipitation | Canopy Throughfall | Streamwater Output: V1 | Net Changes * V2 | Net Changes * V3 |
|---|---|---|---|---|---|
| $H^+$ | 0.22 | 0.34 | 0.16 | 0.04 | 0.05 |
| $Na^+$ | 2.8 | 3.6 | 4.7 | 2.5 (13%) | 1.8 (9%) |
| $K^+$ | 1.3 | 12.8 | 2.7 | 3.0 (1%) | 0.6 |
| $CA^{2+}$ | 4.6 | 6.5 | 5.6 | 1.8 | 3.0 |
| $Mg^{2+}$ | 0.6 | 1.3 | 2.0 | 2.5 (5%) | 1.6 |
| $NH_4^+$-N | 5.1 | 2.5 | < 0.1 | < 0.1 | 0.6 |
| $NO_3^-$-N | 4.0 | 3.4 | 0.4 | < 0.1 | 2.3 |
| N-tot** | 9.1 | 5.9 | 0.4 | < 0.1 | 2.9 (2%) |
| $SO_4^{2-}$-S | 6.8 | 11.4 | 11.6 | 14.3 (8%) | 12.4 (7%) |
| $Cl^-$ | 4.6 | 7.8 | 6.2 | 6.1 (20%) | 5.6 (18%) |
| $HCO_3^-$ | 10.8 | 5.9 | 8.3 | -4.4 | -5.8 |
| Al | 0.09 | 0.22 | 4.04 | 3.15 | 3.30 |
| Mn | 0.06 | 1.31 | 0.81 | 0.40 | 0.42 |
| Fe | 0.08 | 0.14 | 0.47 | 0.0 | 0.0 |

* Percentage of losses of applied elements
** N-tot = Σ $NH_4^+$-N + $NO_3^-$-N

Acknowledgements

The research project ARINUS is jointly funded by the Commission of the European Communities and the Federal State of Baden-Württemberg (PEF, Nuclear Research Centre Karlsruhe, grant no. 86/012/1A). The authors wish to express their appreciation to E. Schöneborn, B. Holzmann, and E. Weber for technical assistance.

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# MIGRATION OF SUBSTANCES IN ALLUVIAL AQUIFER DURING BANK FILTRATION

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## Abstract

Migration processes occurring during infiltration of river water to groundwater was investigated at the experimental site near the Danube River, south-western Slovakia. From the physical point of view, advection is the most significant mechanism affecting the transport of substances within explored groundwater system. Study of heat and major ions transport enabled to examine the structure of groundwater flow.

## 1 Introduction

Much of attention has been focused in recent years on groundwater vulnerability to pollution. Alluvial aquifers can be very easily contaminated by transport of dangerous substances during infiltration of river water to groundwater.

For an understanding of migration processes it is necessary to know the structure of groundwater flow. Field studies under natural conditions enables this, as well in the cases of multidimensional groundwater flow pattern.

The objectives of this paper are to present some results obtained by investigation of stream-aquifer interactions at the experimental site adjacent to the Danube River and demonstrate availability of environmental tracers for study of migration processes in alluvial aquifer recharged by infiltration of river water.

## 2 Theoretical background

Migration of dissolved substances in a saturated porous medium is influenced by various physical, geochemical and biochemical processes. The principal physical processes, which control the transport of substances are advection and hydrodynamic dispersion (Freeze and Cherry, 1979). Both processes are dependent on the structure of groundwater flow velocities. The driving force of advection is the actual movement of groundwater through a porous medium. Dispersion is supposed to represent simultaneously both the molecular diffusion and the mechanical dispersion due to fluctuations of the microscopic flow velocity.

In alluvial aquifers, advection is usually the dominant transport mechanism, hydrodynamic dispersion is playing a minor role. This transport situation is characterized by large Peclet numbers ($Pe > 10$). In addition to the above transport processes, migration of non-conservative substances is influenced also by various geochemical and biochemical processes (e.g. dissolution, ion exchange, oxidation, reduction, microbial degradation, etc.).

## 3 Experimental site

The experimental site for the investigation of physical and geochemical processes during infiltration of river water to groundwater is located approximately 24 km south-east of Bratislava. This is a part of major alluvial aquifer adjacent to the Danube River. The aquifer is composed of unconsolidated gravel-sandy deposits of Quaternary age. High hydraulic conductivity and anisotropy are characteristics of these deposits. The thickness of aquifer at this site is more than 200 m.

Due to the geomorphologic structure of explored area, groundwater in gravel-sandy deposits is recharged by infiltration from the Danube River at every water stage. The direct contribution by precipitation to aquifer recharge is negligible at this site.

Investigation of migration processes during bank filtration has been accomplished on basis of an assessment of data about water levels, respectively piezometric heads, temperature, chemical and isotopic composition of river water and groundwater.

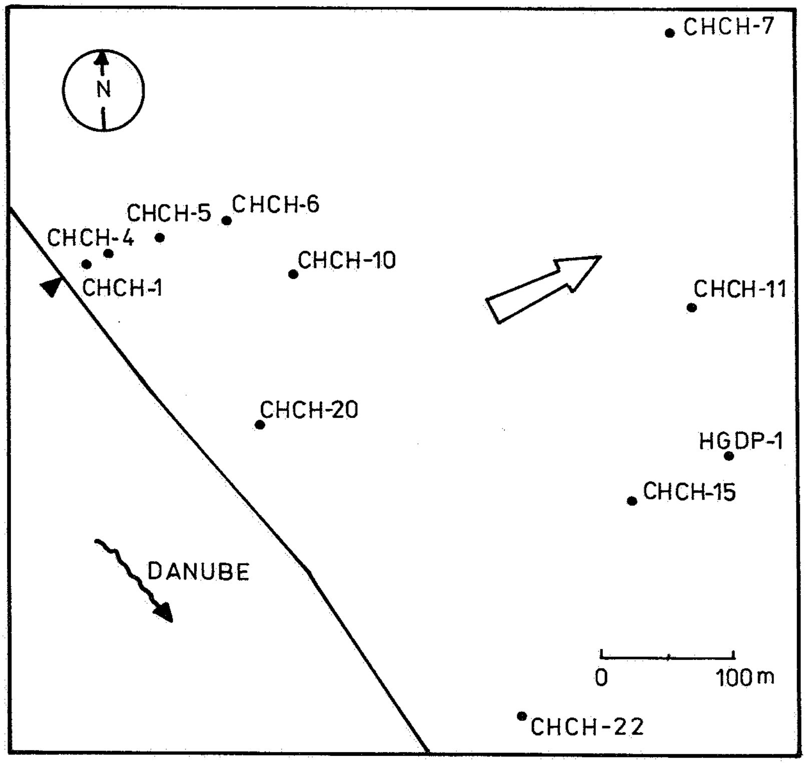


Figure 1. Location of multilevel piezometers at the experimental site

The site has been monitored through a network of multilevel piezometers (Figure 1). Screens were established at the depths of 9, 21, 52 and 99 m. Piezometer HGDP-1 has six screens at the depths of 6, 22, 48, 68, 117 and 163 m. These multilevel piezometers enable to sample at various depth ensuring that no mixing occurs between groundwater of different strata. At this site, infiltration of river water to groundwater and attendant processes have been studied by (Gazda et al., 1983; Lindtner and Šoltész, 1986; Repka and Klaučo, 1986 and Lindtner, 1989).

## 4 Results and discussion

Considering that migration of substances through a porous medium is related directly to groundwater movement, the advective transport should be the first step in the investigation of migration processes. Therefore, it is desirable to know the groundwater flow structure of explored aquifer. The structure of groundwater flow is characterized by flow direction and flow velocity. They can be determined by means of environmental tracers.

In our case, heat was used as a tracer. The autumn is generally considered to be suitable for exploration of spatial distribution of groundwater temperatures. The course of isotherms in the vertical section oriented parallel to the direction of groundwater flow, presented in Figure 2, is characteristic of recharge area. Due to predominant downward groundwater flow, the undisturbed advective heat transport occurs below the theoretical isothermal layer. Considering heat adsorption by solid matrix, the actual average groundwater flow velocity was evaluated using a piston flow model. Its value is 2 8 m/day (Lindtner, 1989). It is obvious that advection is the dominated transport mechanism at the site.

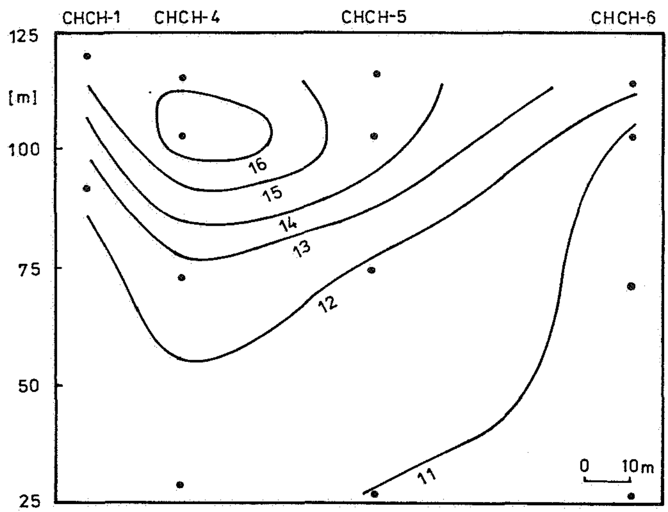


Figure 2. Course of isotherms in vertical section of aquifer on October 1984.

Hydrochemical data were studied chiefly to examine groundwater flow structure over the depth of aquifer. Attention was focused on some of major ions as natrium, magnesium, chloride and sulphate. These substances occur in the form of ideal solution. From March 1988 till May 1989 river water and groundwater in multilevel piezometer HGDP-1 were sampled seven times, approximately in two-monthly intervals. The samples cover an annual variation of ion concentrations; they include minimum as well as maximum water stage.

Chemical composition of groundwater recharged by bank filtration depends primarily on the chemical composition of river water. Moreover, it is altered by various geochemical and biochemical processes along the infiltration flow path.

Changes in chemical composition are controlled by a number of factors, by groundwater flow velocity and residence time among others. Magnesium can evolve under dissolution of dolomite and calcite. Natrium is an exchangeable cation. Sulphate can be released from gypsum and anhydride upon dissolution or is reduced by sulphur bacteria. Only chloride is indeed conservative in its geochemical behaviour.

Seasonal variations of content of each ion were observed in river water. As shown in Figure 3, certain variations occurred in groundwater, too. Seasonal variability in ion concentration is damped by mixing process which takes place in a saturated porous medium. Assuming that the magnitude of damping varies inversely as the Peclet number, it may be said that groundwater flow is the most intensive approximately in the depth to 70 m.

Results obtained by analysis of hydrochemical and temperature data are congruent with previous results obtained using tritium data and numerical modelling (Lindtner and Šoltész, 1986).

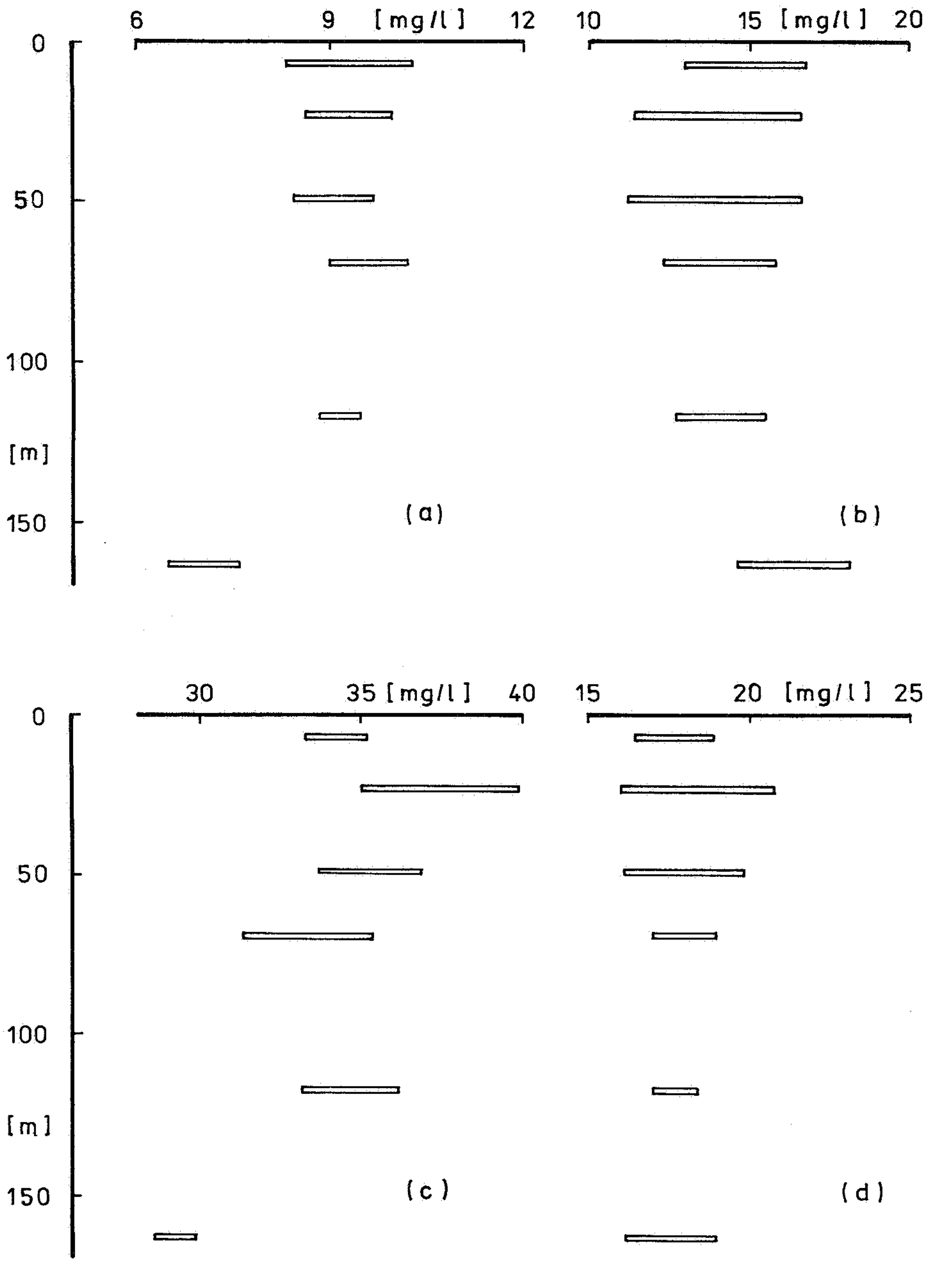


Figure 3. Annual variations of natrium (a), magnesium (b), sulphate (c) and chloride (d) at the multilevel piezometer HGDP-1.

## 5 Conclusions

Study of migration processes during infiltration of river water to groundwater at the experimental site adjacent to the Danube River indicates the following:

- environmental tracers may be used for investigation of transport processes within groundwater flow systems;
- advection is the dominant process controlling the migration of substances in an alluvial aquifer with intensive groundwater flow;
- groundwater in an alluvial aquifer is easily vulnerable to pollutants transported by advection during bank filtration;
- in the recharge area of a major alluvial aquifer, there occurs a vertical hydrochemical zonality corresponding to the structure of the groundwater flow system;
- at this site, groundwater flow is the most intensive approximately in the depth to 70 m.

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# MONITORING WATER AND NUTRIENT BUDGETS IN SMALL MOUNTAIN BASINS: COLLECTING DATA AND/OR UNDERSTANDING PROCESSES?

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Abstract

In 1968 the first of six small partly forested basins in the Alptal valley of Switzerland was equiped with a recording precipitation gauge and a gauging station to measure streamflow continuously. This was the start of an expanding monitoring activity. During the past 21 years more basins and more parameters were added to the observation program, but considerable reductions together with increased intensity of the measuring network have also taken place. Sensors, monitoring techniques, analytical procedures, operational organisation and personnel have also changed. The question of how the monitoring data can serve the understanding of processes is treated by looking at quality control of raw data, by doing plausibility calculations, by calculating individual components of the water and nutrient budgets, by characterizing the hydrologic behaviour of the basins and by using models or doing process studies in the field or laboratory. Examples demonstrate the respective importance. It is shown, that monitoring alone is of little value, unless a continuous analysis and tests for methods and trends give good quality control of the data collection system.

## 1 Introduction

In recent years good data from well monitored longterm research sites are frequently needed to demonstrate quantitatively what the status of the environment was or is regionally or locally. To make measurements of today's situation is one thing; if however, trends for changes are sought, the problem of monitoring becomes much more delicate and difficult. It is easy to find errors and mistakes today and to say how things should have been done yesterday.

The purpose of this paper is to look back at a 21 year study, at changes in technical aspects, research questions and aims of investigations during the years. We try to analyse the situation to the extent that we become aware of what we would and would not do again.

## 2 Some Historic Aspects of the Alptal Study

When the first very simplistic gauging stations as part of the Alptal study (situated in the northern Prealps of Switzerland) were built we had little experience in doing monitoring work. We knew, that we made mistakes, but we also had much energy and enthusiasm for doing something, eventhough knowledge was not perfect. The main aim was to establish the relations between precipitation and streamflow in small torrent basins of a hydrologically little known area. What is the role of forests? How much water is used by forested basins compared to a basin in pasture and nonforested wet lands? We had little finances and we were marginal with personnel. Yet we managed to construct gauging stations in 1968 (Vogelbach 3), in 1969 (Gämschbach 7), in 1970 (Frifang 5), in 1971 (Etterenbach 8), 1972 (Lümpenenbach 4) and in 1973 (Erlenbach 10). At the same time we established a precipitation network with 2 recording instruments and 2 storage gauges in each of the 6 basins. Almost all of our time was put into field work, building and maintaining stations, cleaning after floods, keeping the installations from freezing in winter, calibrating measuring channels, etc. There was no 'winter break' to do data analysis, to make monthly and annual water budgets, to decide on rating tables etc. About one year behind we put the streamflow data on punch cards, still leaving uncertainties about the conversion of water levels to discharge volumes. Eventhough twice a month instantaneous streamflow measurements were routinely taken, we missed many high flows which we needed for the construction of a reliable rating table. We have learned since, that irregular gauging, in particular timed for high flows, is more satisfactory for the purpose of establishing a stage - discharge relationship. Another problem was and still is the correction for bed load transport. Since there are no sediment basins upstream of the gauging site (except Erlenbach 10 since 1982) the water level should be corrected for water flow only. But how? These are additional reasons which made it difficult to estimate the water balance components.

In addition we wanted to know the mineral and nutrient content of the discharging water from forested and nonforested basins. Therefore we started to take weekly grab samples, one liter at each gauging site, and carried it to the laboratory to get the analytical results a few months later for further use in the study. Estimating loads proved to be very difficult, particularly for elements which were not related to the rate of discharge. Finally with much effort and still much uncertainty the first publication went to the printer in 1970 (see Keller 1985). Today we look back at a period of which we are pleased it is over. It cost us much patience because we had to wait so long for working up the data, to do plausibility and comparisons and to join up the quantitative and qualitative data from the various sources.

## 3 Changes

In the late 70's questions as well as methods started to change. Earlier, the purely quantitative hydrologic role of the forests was not concerned with information on dissolved solids discharge, but now new questions have started to concentrate on deposition, rain and snow chemistry, interception and through fall chemistry as well as a continuous monitoring of nutrient and mineral discharge in addition to the grab sampling concept.

The flood in the summer of 1974 damaged or destroyed most of the gauging sites. With the personnel and finances available it was sad, but clear to see, that we would not be able to continue. We were more or less forced to rethink and work out a new concept. Therefore we decided to cut the number of stations to 3 and to do much more intensive monitoring with fewer and physically stronger gauging

structures which should withstand the floods better.
This is why station 3 and 4 were rebuilt and taken into operation again in 1975. Station 10 was chosen to become a pilot installation for torrent as well nutrient studies and was completed in 1982. Since then many new monitoring techniques have been applied to these 3 stations, and today we are pleased to have a 10-minutes automatic logging system which transmits daily, by telephone line, climate as well as streamflow data to the institute headquarters in Birmensdorf, allowing a daily check and plausibility test on sensors and status of the hydrologic system. What had taken a year in the late 1960's can now be done in a day. However a few serious problems remain:

- the field calibration of the gauging stations for high flows is still uncertain (automatic gauging is in preparation);
- continuous bed load transport measurements are practically not possible yet (tests are under way).

In summary we made a dramatic experience with our first measurements and slow data return organisation. We were fully engaged with data collecting and had hardly time to think over why we were doing what.
Today we know what we have learned by experience; we had little changes in personnel and have been able to make technical advancements. This saves much time, intensifies information and the most important of all: we are able to make almost on line inferences from data bank systems. We can quickly answer questions and have time to think about processes, conduct appropriate studies, and are able to explain monitoring results. In the future we plan to study trends in the behaviour of the hydrologic basin ecosystems. It will not be easy since we had a number of changes in methodology, sensors and data collecting systems.

## 4 Comparative Hydrologic Behaviour

With the present installations and data techniques available much more on plausibility could be done than we do now. Limits on time, personnel and finances let us do the most necessary only. We therefore try to aim for a good documentation from field, laboratory, data bank and data analysis. This is a prerequisite for later detailed work and is unfortunately often overlooked. Studying now the longterm evolution of the basins based on the available data, we find ourselves over and over again in underdocumented situations, although at the time we were taking the measurements we were careful to do a perfect and complete job.

Some of the available data on quantity and quality as well as simulation model results should - in the following section - show how we try to do comparative hydrology, to link the many information sources and to try to explain some of the observed 'anomalies'.

## 4.1 Nitrates in Streamflow

In Fig. 1 the various sources of nitrates in streamflow of basin 3 are shown from 1968 through 1988. Arithmetic mean annual concentrations from weekly grab samples are generally higher than the discharge weighted averages. The years 1984 and 1985 seem to be exceptional. The data from the weekly flow proportional composite samples are shown since 1986. What are the reasons for the difference?

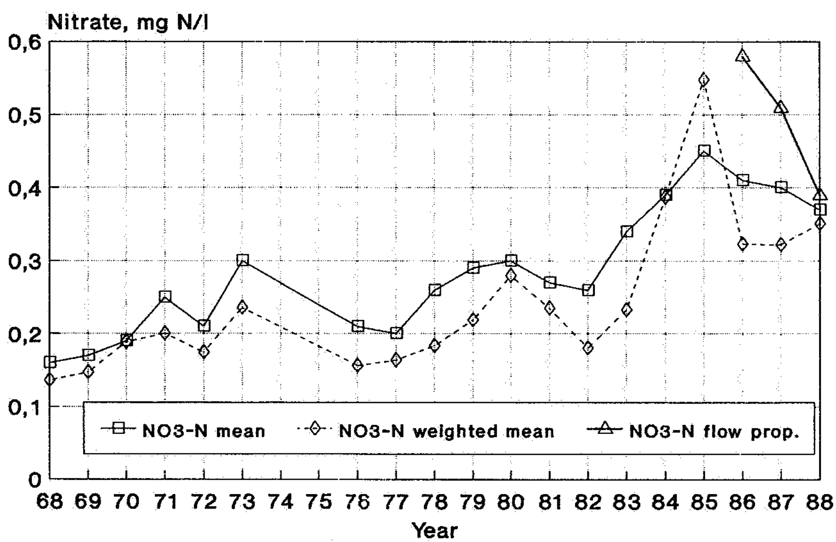


Figure 1. Nitrate concentrations in streamflow at basin 3 from 1968-88, calculated as arithmetic and flow weighted mean from grab samples and from weekly flow proportional composite samples.

To find reasons we studied the seasonal distribution during the time since installation of the flow proportional sampler (Fig.2). It seems that in late summer and autumn the differences seen earlier are most obvious. The search should now continue by looking in particular at the August data, etc. Where do we end? We will probably find a few data points which appear to be questionable and finally we won't know whether our measurements were wrong, or if we measured a special event with one method and missed it with the other. There are many more similar plausibilities to do. Why don't we take the time to do it all?

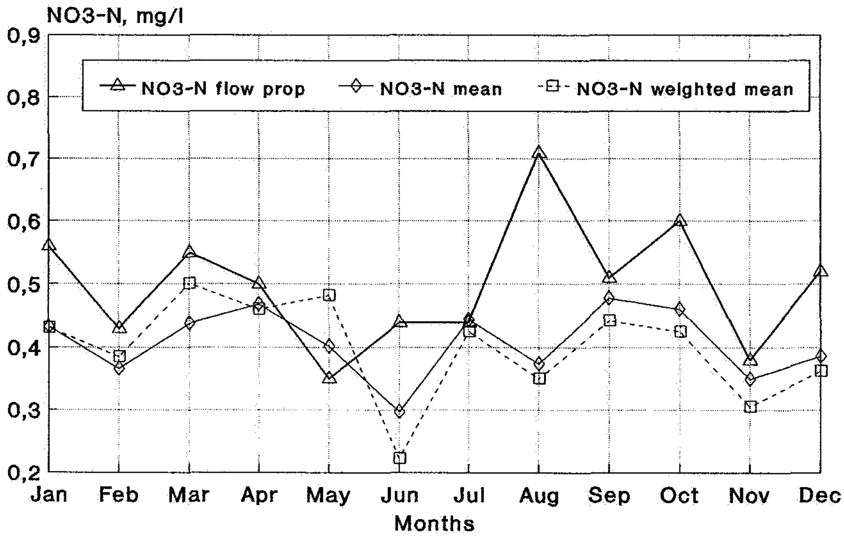


Figure 2. The seasonal variation of nitrate concentrations in streamflow of basin 3, 1985-88 using the same methods as in Figure 1

## 4.2 Components of Streamflow and the 'Dilution' Effect

From weekly instantaneous as well as from flow proportional sampling, typical dilution effects are observed in the study basins. Figure 3 shows Na concentrations for one of the mentioned sampling schemes in basin 3 and 10. This relationship suggests that at low flows Na is derived from deep subsoil sources, which are more or less rich in Na. At high flows however, the baseflow waters are diluted with waters from

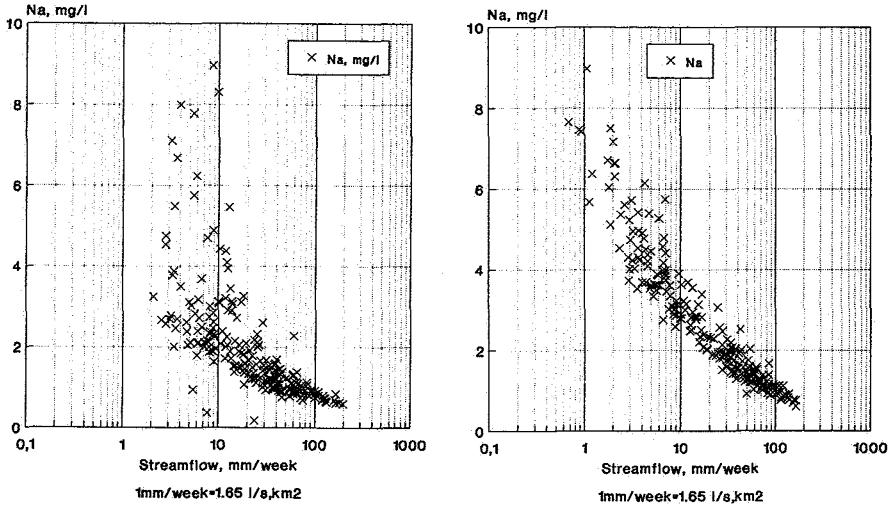


Figure 3. Streamflow volumes and Na concentration in weekly flow proportional samples at basin 3 (left) and 10 (right)

near surface sources which contribute considerably less Na. In order to test this hypothesis we used the result of the water balance simulation model BROOK (Federer and Lash 1978, Forster 1989) which distinguishes mainly 3 sources of streamflow: surface flow (including snowmelt), interflow, and groundwater flow (baseflow). The result of the multiyear simulation runs on a daily time step in basin 3 and 10 are given in Table 1. The flow components are obviously different. The interflow in the well forested basin 3 with relatively deep soils being considerably higher than in basin 10 with much less forest area and generally more shallow soils.

Table 1 Components of Streamflow, estimated from the simulation model BROOK, annual summaries.

| | Surface Flow | Interflow | Groundwater Flow |
|---|---|---|---|
| Basin 3 (%) | 44 | 45 | 11 |
| Basin 10 (%) | 64 | 29 | 7 |

What is the reason for the wide scatter of Na concentrations at medium flows in basin 3 (see Fig. 3)? Are there analytical problems? How can we check the plausibility? Could the smaller scatter at medium flows in basin 10 (Fig. 3) be linked to the small contribution from interflow? How should interflow be defined? Is the above stated hypothesis worth testing?

Another link between flow components and relationships shown in Figure 3 is seen in the degree at which the concentrations decrease. A change in flow from 10 to 100 mm/week corresponds to a decrease of about 1 mg Na/l in basin 3, and of about 2 mg Na/l in basin 10. The latter indicates a fast dilution from surface flow. In basin 3, however, with less water from near surface origins, the dilution appears less pronounced.

## 5 Conclusions

Every research project has its history, aims, priorities and changes. The example of a longterm multi-basin study shows that researchers are not always free to do what they planned to do. When the aims change, it is difficult to follow the longterm continuity.

Our experience is therefore not to do monitoring for its own sake. Data should always mean something and one can hardly do enough for testing the data and doing plausibility tests. This work brings the scientist close to the real world. Excellent hypotheses on processes are often born in a plausibility study testing monitoring data. Monitoring is the key to process-studies and good process-studies need a link to monitoring.

## 6 Acknowledgments

I like to thank all my past and present colleagues for their enthusiastic activity in this longterm project; in particular Walter Hofstetter for field work and data compilation, Paul Weibel and Maria Guecheva for analytical work, Felix Forster for simulation calculations, Hans Burch for handling the data banks and Bruno Fritschi for updating the technical installations and data transfer methods.

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# A BASIN STUDY FOR POLLUTANT TRANSPORT

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## Abstract

A multidisciplinary research project has recently been initiated to study transport processes in rural areas. It consists of development and calibration of a numerical model for describing transport processes of water, eroded soil, fertilizers and other naturally occurring or anthropogenic substances for a small rural catchment. Model development is accompanied by an extensive field study, for which a loess catchment, the Weiherbach catchment near Karlsruhe has been selected and instrumented. Conception of the project and first results are presented.

## 1 Introduction and survey

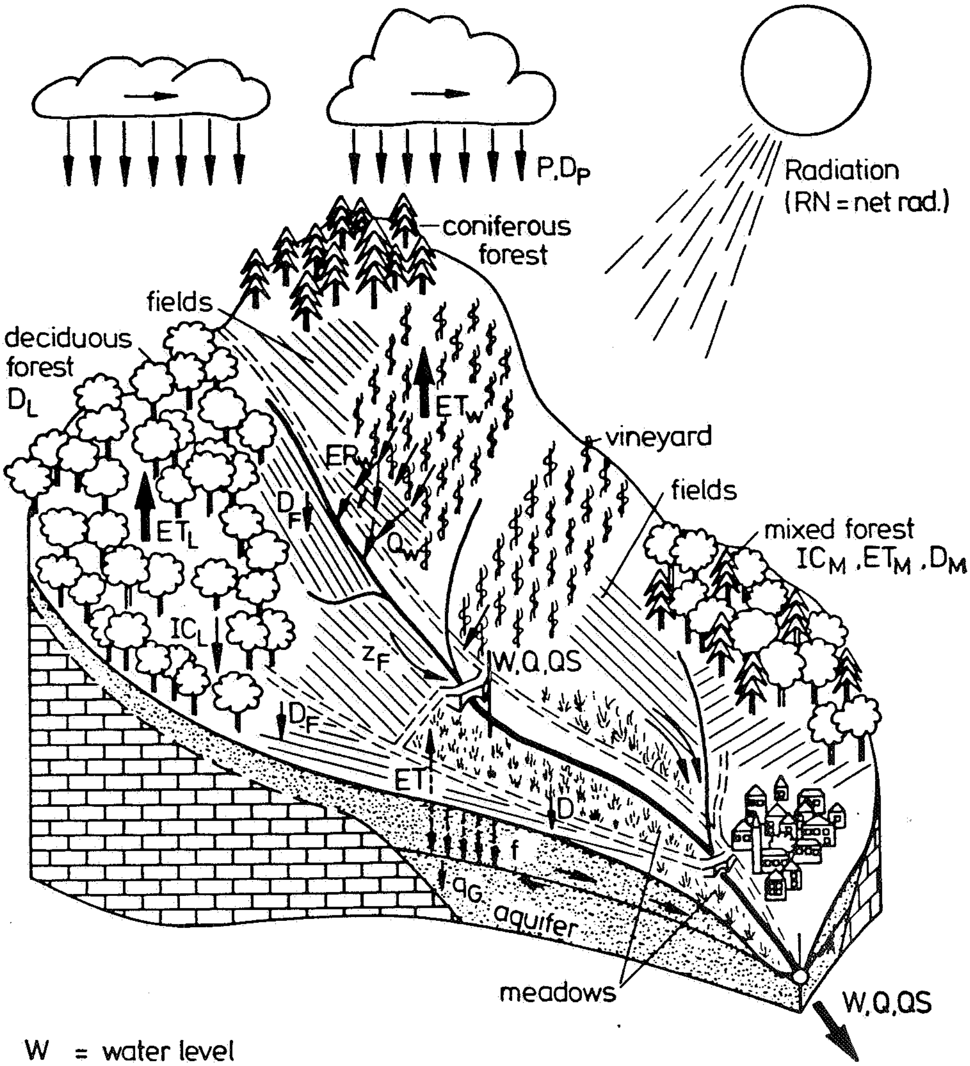
Pollution of ground- and surface waters can have serious consequences for water users and ecology. Examples are the noxious effects to health, caused by high nitrate concentrations and the epidemic two years ago which resulted in hundreds of victims in the seal population of the North Sea. Especially the modern agricultural practices with massive use of fertilizers and pesticides have been criticized. Another source of water pollution - besides the effluents from industrial plants, deposits and sewage plants - is the immission from the air.
The quantification of material transport in an agricultural region must be based on a detailed description of the transport of water from a

heterogeneous area covered with agricultural fields and forests, which determines the runoff of matter. A model for these processes must reflect the diversity of utilization of the land, and the different amounts of fertilizers and other substances that are applied for different types of crops. It also must reflect the variety of the soils that are found in the region, and the geological structure of the underlying subsoil, which will determine the amount of fertilizer-carrying water percolating into the groundwater. And it will be influenced by the topography of the region, with the runoff characteristics of flat lands quite different to those of rolling country.

A typical rural region may show the diversity depicted in Figure 1, which is an artist's view of a small agricultural and silvicultural area similar to many found in rural Germany, and which may cover an area of a few square kilometers. It is apparent that only in exceptional cases it will be possible to describe runoff characteristics of water and pollutants from such an area by a completely deterministic model. Such a model is to be developed in a multidisciplinary study called the "Weiherbach Project", on which 12 institutes of the University of Karlsruhe, one institute of the University of Heidelberg, and the State Agricultural Research Station of Baden-Württemberg are cooperating.

The input level of the model consists of parameters which describe the area as well as transport features. The basic variables needed for modeling are those describing natural properties of the area, such as topography, geology, soil characteristics, and land use characteristics. At present, these characteristics have to be obtained from field surveys or from topographic maps. In future much of this information will probably be obtained from remote sensing, from satellites or from aerial photographs. It is stored in computer-based information systems, such as Geographic Information Systems (GISs). These basic data are sufficient to specify the properties of water and matter transport for long term averages. They may also be transferred to larger areas, perhaps by including data from local calibrations.

Superimposed on these basic variables are the seasonal variables, which will provide the background information for the event-based model, but which might also be used to determine average seasonal balances. Both




W = water level
P = precipitation
ET = evapotranspiration
IC = interception
f = infiltration
z = erosion from field
q = runoff from surface
Q = discharge of creek
D = vector of pollutant inputs ($D_P$ from precipitation)
QS = vector of pollutant transport
ER = erosion yield

Index P = precipitation
F = field
W = vineyard
L = deciduous forest
M = mixed forest
N = coniferous forest
G = ground water

Figure 1. Schematic view of a heterogeneous small scale agricultural region (by E. Plate)

seasonal and permanent data stored in a GIS can be represented on maps by application of geostatistical methods.

The actual dynamics of the transport must be generated from event-based information, such as actual or historical rainfall events, or time series of precipitation which have been generated by Monte Carlo techniques. Event inputs include input of matter into the hydrological system, such as fertilizer inputs, or inputs through accidental releases of toxic or harmful substances. The event-based model yields most detailed output information but also requires most input data.

If this type of model is used for long term application, we would have to deterministically calculate the flow of water and matter at one or more points of the area to obtain a continuous record of output functions. It is obvious that such a model, which will permit long term simulation of actual occurrences of polluting episodes, is expensive to use and time consuming to construct, and therefore it can be applied only in exceptional circumstances - for example, during our Weiherbach study.

Actual operational models will have to be simplified. The degree of simplification is to be determined by the purpose of the model and the available data. Models of different degrees of complexity are needed for different purposes: for example, a comparatively simple mass balance model is sufficient to describe annual average soil erosion in order to predict the effects of changing land use and agricultural practices, whereas a model which is to predict short term and local effects of accidental spills needs a complex transport model.

## 2 Project organization and first results

The institutions cooperating in the project represent the following disciplines: meteorology, geography and geoecology, geology and geophysics, mineralogy, remote sensing, computer and information sciences, agriculture, microbiology, water chemistry, hydrology, hydraulics, and agricultural engineering. To organize a program involving so many different institutions, of which each has its own traditions, points of view, and methods, into a coherent frame requires a well functioning organizational structure.

Such a structure has been developed from the beginning. The project planning started with a conceptual model of the study by the Institute for Hydrology and Water Resources Planning of the University of Karlsruhe, and according to the needs of this model a group of institutes were invited to participate in the study and to submit a proposal on the aspect of the study which was assigned to them. The proposal was funded in November 1988 on this basis. The project is administered mainly in regular meetings of the project group, which decides on all important group activities, such as acquisition of data handling equipment, the structure of the databank, and the selection and installation of joint field stations. The original conceptual model was used to prepare a schedule of activities including experimental programs for each member within the group activities.

For each of the tasks involving organizational decisions small working groups consisting of the interested scientists are formed which prepare the decisions and present their findings to the project group. Such working groups are formed for selection of the hillslopes to be instrumented, on the distribution of measuring points, on surface runoff, on soil characteristics of the region, on soil water measurements, on water chemistry and biology, on databank and GIS, on numerical modeling, and on project documentation.

The first steps in meeting the objectives of the Weiherbach project are (1) modeling overland flow and mass transport from individual hillslopes and in the creek, including modeling water and material transport through the unsaturated zone down to the groundwater level, and (2) selecting a study area and setting up a measurement system, and (3) developing a suitable Geographic Information System and databank for keeping and editing the basic information in vectorial or grid form, in order to permit collecting space time information at appropriate scales and storing it for easy access and future manipulation.

The model concept for modeling hillslope processes is described in a companion paper by Bronstert (1990). To develop a complex model, the catchment is subdivided into many homogeneous subsections, called hillslopes, and characteristics of pollutant and fertilizer transport are modeled for each of these slopes. The model is developed for different types of hillslopes, for which typical areas are selected in


Figure 2. Topographic map of the Weiherbach area showing the locations of precipitation and runoff gauges

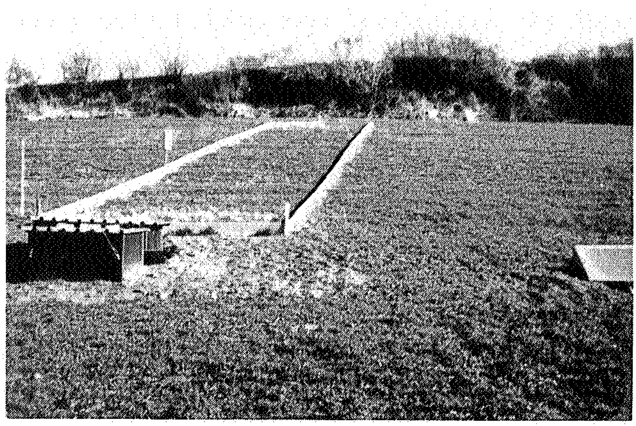


Figure 3. Runoff plot installation on a test hillslope (photo by M. Schramm, IWK)

the test region. Other computer models for component processes are developed, and intensive measurements on several hillslopes and throughout the whole study area are carried out and samples are analyzed to provide calibration data, which are stored in the databank and used in the GIS.

Most of the field work started in summer 1989. The main activities were: Selection of the study area, fixing the measuring points and fields, building and equipping them, taking samples, measuring variables and analyzing them, and establishing concepts for the databank and GIS. The Weiherbach catchment selected for study is a loess area of some 6 square kilometers situated in the Kraichgau region 30 km north-east of the city of Karlsruhe. Figure 2 shows a map of the study area, in which the locations of some sampling points are indicated, and Figure 3 shows some of the installed equipment. These typical sections are instrumented for intensive field studies, which are to be used to provide data for calibrating model components. We are studying the transport processes from (polluted) rainfall and fertilizer application on every field to runoff and concentrations of substances ranging from fertilizers to pesticides and heavy metals in the Weiherbach creek. Also the transport in the unsaturated zone is investigated. The region is very susceptible to soil erosion, and the amount of soil entering the creek and eroded from the test slopes is also measured.

As basic information the following items are investigated and corresponding data are provided: topography, drainage network with flow profiles, land use categories, geology, soil types and soil parameters. A large variety of time variant characteristics are measured, analyzed and partly processed, e.g.:

- precipitation, evapotranspiration and other meteorological data from a central measuring station and 6 other rain gauges;
- deposition from the air and application of fertilizers and pesticides;
- infiltration, soil moisture and chemical parameters in the upper soil zone and approximately 60 points in the catchment area;
- soil moisture, water tension and groundwater recharge in the lower unsaturated soil zone at 3 hillslopes, together with measurement of other variables to calibrate the hillslope model;

- transport of soil material from erosion test plots at several sites in the catchment;
- runoff, transport of sediment and chemical substances in the watercourses.

Some first results of the joint efforts are presented in the companion papers by Bronstert (1990) and Schiffler (1990). The concepts developed for hillslope are described by Bronstert (1990). A special report on the soil moisture measuring network is given in the paper by Schiffler (1990).

## 3 Outlook for the future

The results of the study should form the basis for operational models. Our long term objective is to develop a PC-based model which can easily be adapted to the needs of a special application in other areas than the one for which it has been developed. It is our intention to investigate how much a complete model, such as the Weiherbach model to be developed, can be simplified, and still be applicable, or in other words one has to find out how many of the parameters of the problem are truly important, and which are not. This implies trading off variability from a deterministic model with many parameters against a simpler model with less parameters, but with a certain larger degree of stochasticity, and which is simplified to meet the purpose at hand and to take cognizance of the limited data base which is available in the area for which the application is intended. Such a model may require the inclusion of statistical models in lieu of deterministic components.

## Acknowledgements

The Weiherbach study is supported by funding from the Federal Ministry for Research and Technology (BMFT). Thanks are also due to the many colleagues cooperating in this multidisciplinary project.

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# MODELLING THE IMPACT OF AGRICULTURE UPON WATER QUALITY IN THE WINDRUSH CATCHMENT - AN EXPORT COEFFICIENT APPROACH IN A REPRESENTATIVE BASIN

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Abstract

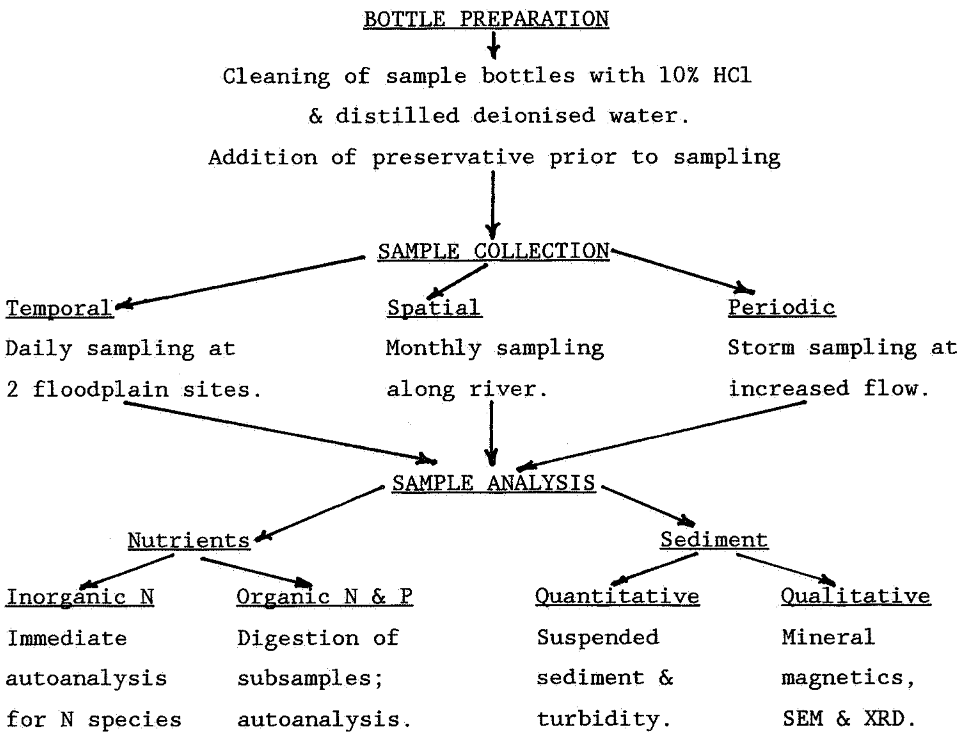
A distributed export coefficient model of nitrogen, phosphorus and sediment loss from a catchment of mixed land use is presented. The River Windrush was selected as a representative basin for this study. A land use survey was used to calibrate the model and the results of a 3-year fieldwork programme, together with archival material provided by Thames Water Authority, were used for validation. The approach allows identification of export zones, and evaluation of potential pollution control strategies.

## 1 Approach

The approach taken in this study involves the application of an export coefficient model in order to predict nutrient and sediment loading on the aquatic system of a drainage basin. This approach has been developed by a number of authors (e.g. Beaulac and Reckhow, 1982; Delwiche and Haith, 1983; Rast and Lee, 1982; Jorgensen, 1980; Vollenweider, 1968; Johnes and O'Sullivan, 1989). Information is required on nutrient and sediment sources in the catchment, and independent water quality data are needed for model validation.
The Windrush, a tributary of the Thames, was selected as large enough (350 $km^2$) to assess fully the capabilities of this approach at a

realistic scale for catchment management. It is also representative of a wide range of predominantly rural lowland basins with mixed geology and land use, and a relatively low population density.

A sampling strategy was designed to allow temporal, spatial and periodic sampling of the river at a range of sampling sites, and operated over a 3 year period to provide data for model validation:




A new technique was developed for the digestion of organic nitrogen and phosphorus (Heathwaite et al., in prep.); standard autoanalytical techniques were used for subsequent analysis. SEM and XRD were conducted at the University of Reading. These data were supplemented by Thames Water Authority records of water quality and discharge for the River Windrush commencing in 1972. Results from the sampling programmes are presented in Figures 1 and 2.

Agricultural inputs to the drainage basin were calculated from past and present surveys of fertiliser practice (AFRC, Rothamstead), annual agricultural returns (Public Records Office, Kew), and a questionnaire

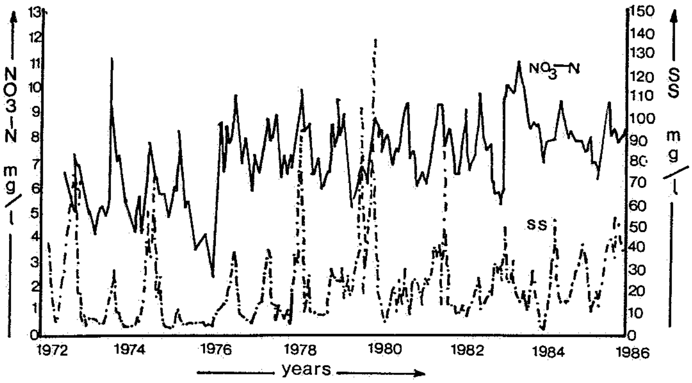



Figure 1. Nitrate and suspended sediment concentrations for the windrush: 1972 - 1986

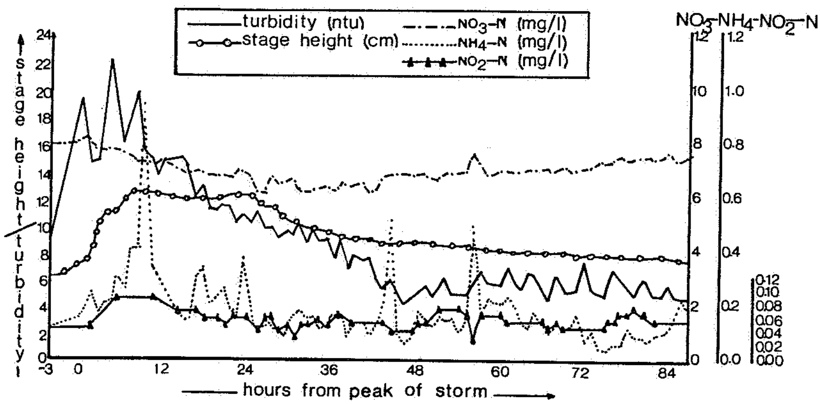



Figure 2. Sediment and nutrient dynamics for storm of 16/09/89

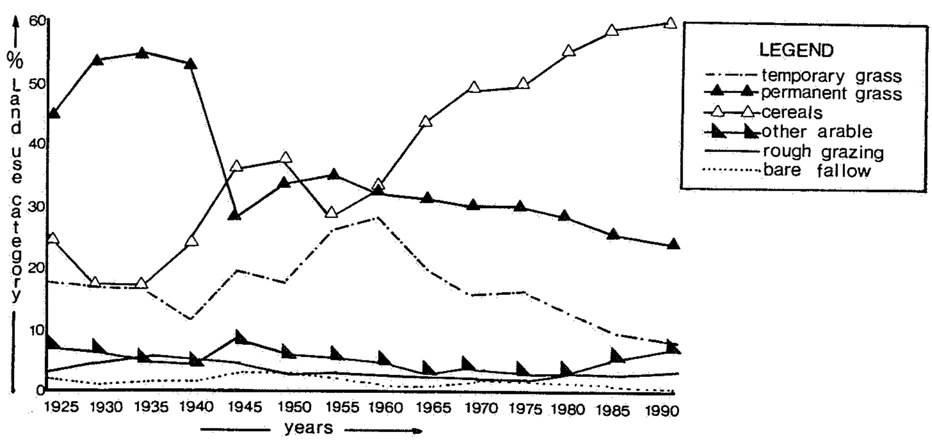



Figure 3. Land use in the windrush catchment: 1925 - 1990

survey of all farmers and land owners in the catchment (Figure 3). Atmospheric and cultural (i.e. domestic and industrial) inputs were derived from published values, excluding those for sewage works which were obtained from the local Water Authority.

Losses from the catchment were computed using an export coefficient model for which a range of nutrient export coefficients were derived from the literature for each model parameter. Initial loss coefficients and values used for N & P content of livestock wastes (e.g. Gostick, 1982; Vollenweider, 1968) are presented in Tables 1 and 2. Preliminary results for predicted annual nitrogen and phosphorus exports derived from the model are presented in Table 3.

Table 1. Loss coefficients for manure and fertilizer (% a-1)

| ORGANIC | N | P | INORGANIC | N | P |
|---|---|---|---|---|---|
| Cattle | 16.15 | 2.85 | Grassland | 5 | * |
| Pigs | 17.00 | 3.00 | Cereals | 12 | * |
| Sheep | 14.15 | 2.60 | Other tillage | 30 | * |
| Poultry | 15.30 | 2.70 | | | |
| Horses | 16.15 | 2.85 | | | |

* general loss of inorganic phosphorus 0.1 kg $ha^{-1}$ $a^{-1}$

Table 2. Characteristic loadings of N & P in manures

| | Loadings kg $ca^{-1}$ $a^{-1}$ | | % Manure | | % Lost | % total |
|---|---|---|---|---|---|---|
| | N | P | Directly voided | Stored in barns | during storage | applied to land |
| Cattle | 70.20 | 7.65 | 50 | 50 | 10 | 95 |
| Pigs | 18.75 | 5.63 | 0 | 100 | 15 | 85 |
| Sheep | 8.90 | 1.50 | 100 | 0 | 0 | 100 |
| Poultry | 0.30 | 0.20 | 0 | 100 | 10 | 90 |
| Horses | 76.80 | 11.40 | 50 | 50 | 10 | 95 |

Table 3. Predicted losses of agricultural nitrogen and phosphorus from the Windrush catchment (Tonnes $a^{-1}$)

| Year | Inorganic | | Organic | | Total | |
|---|---|---|---|---|---|---|
| | N | P | N | P | N | P |
| 1990 | 475.01 | 2.72 | 592.46 | 91.63 | 1067.47 | 94.35 |
| 1985 | 468.96 | 2.79 | 590.59 | 94.59 | 1059.55 | 97.38 |
| 1980 | 368.45 | 2.77 | 653.96 | 101.25 | 1022.41 | 104.02 |
| 1975 | 260.15 | 2.77 | 765.91 | 116.01 | 1026.06 | 118.78 |
| 1970 | 202.04 | 2.77 | 628.99 | 93.54 | 831.03 | 96.31 |
| 1965 | 140.00 | 2.77 | 629.25 | 98.69 | 769.25 | 101.46 |
| 1960 | 129.14 | 2.76 | 647.48 | 96.80 | 776.62 | 99.56 |
| 1955 | 96.24 | 2.71 | 640.09 | 93.68 | 736.33 | 96.39 |
| 1950 | 66.14 | 2.69 | 571.16 | 79.21 | 637.30 | 81.90 |
| 1945 | 58.40 | 2.63 | 476.02 | 64.06 | 534.42 | 66.69 |
| 1940 | 33.50 | 2.65 | 564.24 | 85.31 | 597.74 | 87.96 |
| 1935 | 31.81 | 2.65 | 512.11 | 80.11 | 543.92 | 82.76 |
| 1930 | 34.89 | 2.67 | 366.89 | 57.72 | 401.78 | 60.39 |
| 1925 | 39.86 | 2.69 | 477.29 | 69.53 | 517.15 | 72.22 |

Optimisation of the model is currently in progress. This will allow selection of a best fit combination of coefficient values, modification of equations and incorporation of time lags where appropriate. Validation will be achieved using water quality data generated from the fieldwork programme, those obtained from the Water Authority, and data from the survey on past land use and management in the catchment.

Spatial analysis of the basin is currently being conducted using the SPANS Geographical Information System. This will combine the land use survey; information on soil type, geology, topography, drainage network and urban areas derived from Ordnance Survey maps, and Water Authority records of dredging, trimming and gravel bed excavation in the river bed and bank-side zones. This technique will allow identification of major zones of nutrient export and of important sediment source areas within the catchment. Spatial trends in water quality with respect to nitrogen, phosphorus and sediment collected over the field research period will be used for validation of the GIS spatial analysis. This analysis thus permits identification of sensitive areas for subsequent catchment management with a view to implementation of pollution control measures.

## 2 Results

Analysis of the long term records of water quality (1972 - Thames Water Authority) indicates clear upward trends in nitrate and suspended sediment concentration. Statistical analysis indicates that whilst the increase in suspended sediment may be attributed to a run of drier years in the 1970s followed by a sequence of wetter years, the nitrate trend is more strongly time-dependent rather than being controlled by climatic variations.

Quantification of in-stream nitrogen fluxes for short-term, seasonal and annual time periods (Figures 1 and 2) has permitted assessment of how representative each is as an indicator of total nitrogen loading in aquatic systems. Results show a flow-dependent relationship for the various nitrogen species with nitrate as the dominant ion. Clear seasonal trends are exhibited by data from both daily sampling sites (Table 4).

Table 4. Seasonal trends in nitrogen species & suspended sediment concentrations

| Month | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SUS.SED. | high | | > | | | | low | | < | | high | |
| NITRATE | high | | > | | | | low | | < | | high | |
| NITRITE | low | | < | | | high | | | > | low | | |
| AMMONIA | low | | < | | | high | | | > | low | | |

Thus nitrate and suspended sediment concentrations correlate on a seasonal basis, as do nitrite and ammonia concentrations. Ammonia and suspended sediment concentrations are directly linked during storm discharge. Preliminary results show that organic nitrogen is correlated with reduced forms of nitrogen ($NO_2$-N and $NH_4$-N) with higher concentrations in summer and autumn, and that generally, organic nitrogen and nitrate are inversely correlated during storm flow. Interchange between nitrogen compounds in freshwater, in relation to flow and seasonal variation appears to be an area meriting further attention. Total nitrogen and phosphorus levels rather than those of individual ions will be used for model validation in this analysis (Johnes, in prep.).

Qualitative analysis of suspended sediment and turbidity at spatial and temporal scales has permitted identification of sediment sources in the catchment. SEM and XRD conducted on filtered sediments from spatial samples indicate the presence of smectite linked with a Lias clay origin as the main source of the turbidity observed in the River Windrush during the summer (University of Reading). Field monitoring of river turbidity indicates that this occurs after storm events and remains in suspension for long periods at low flow. Comparison of findings with analyses conducted on catchment sources (river bed and bank sediments, ploughed land, areas of livestock poaching, urban areas and exposed bedrock), together with the land use survey suggest that ploughing of the Lias clay floodplain, field drainage, and intense erosion of the bed and banks through active meander stretches are key causal factors of the turbidity in the summer. Further analysis using SPANS will permit identification of particular catchment zones for possible implementation of pollution control strategies to reduce turbidity.

## 3 Conclusion

The approach adopted in this study has allowed basin-scale evaluation of the impact of past and present land use and agricultural practice on losses of nitrogen, phosphorus and suspended sediment from the Windrush catchment. Such methods may be applied to other drainage basins, and used for a wide range of water quality parameters. The model itself may be directly applied to basins of the type represented by the Windrush catchment. It is hoped that these results will form the basis of pollution control strategies designed to meet specific water quality objectives, including those proposed for Nitrate Sensitive Areas.

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# A CONCEPT FOR MODELLING MATERIAL TRANSPORT IN A SMALL RURAL CATCHMENT

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## Abstract

The concept for an operational computer model to simulate water and material transport in a small rural catchment is presented. The model includes a subdivision of the catchment area into a net of slope segments. All significant hydrological processes are considered separately and modelled in the scale of the slope segment. Simulation of material transport will be based on the linkage of the substances' transport patterns with the relevant hydrological processes.

## 1 Introduction

Main objective of a comprehensive research project located at Karlsruhe University and financed by the German Ministry for Research and Technology is to balance the water and material transport of a small rural catchment. An operational computer model is being developed to simulate transport processes in the watershed and to predict the material outflow of the whole catchment. The model shall be used to evaluate possible consequences of e.g. changes in specific land use, use of pesticides or accidental point pollutions as well as to estimate the chemical load out of a rural catchment.

The data necessary to develop and calibrate the model are collected in the extensively measured Weiherbach Catchment. It is an intensively farmed, hilly area of about 6.3 km$^2$ size, northeast of Karlsruhe in SW-

Germany. Buck (1990) and Buck and Plate (1990) give an overview over the whole research project, which is formed of 15 sub-projects, a number of them investigating a specific hydrological and/or chemical process. The concept of the simulation model presented in this paper emphasizes, that inter-flow plays an important role in inducing catchment runoff and that surface runoff is caused at least partly by saturation excess. These points have not been stressed on in other hydrochemical models, e.g. the CREAMS, as described by Smith and Knisel (1985).

## 2 Catchment Subdivision

Simulating the water movement as well as the transport of point and non point source pollutants requires a physically-based distributed model. Hence the catchment has to be subdivided into a number of adequate segments. Considering the natural topographic, pedological and agricultural conditions, instead of an uniform grid-type subdivision a discretization into size- and shape-variable units ('slope segment') is proposed. This way of discretization is of particular use for hilly areas.

The subdivision procedure has to be performed (by using an adapted geographical information system) in a way which yields to a certain degree of segment homogeniety, regarding topography, pedology and land use. Furthermore the channel network and road system has to be taken in to account. Figure 1 shows the schematic catchment subdivision.

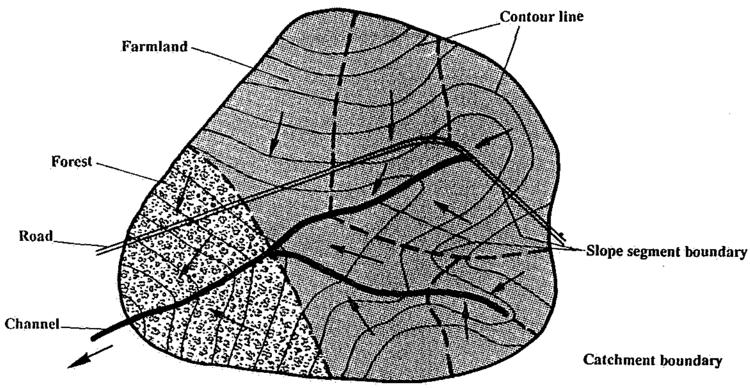


Figure 1. Schematic representation of catchment subdivision

On any segment the slope model can be applied, simulating the water and material movements within this area. The slope segments are connected either with the adjacent segments or discharge laterally into the channel. Both the channel network and the interconnected segments represent the modelled catchment with regard to its field-scale heterogeneity.

## 3 Modelling the water movement

Water is the medium for all significant transport processes within a catchment. Description of flow path and residence time within the soil or on the soil surface is the base to model material transport and therewith material outflow of the considered spatial unit. A schematic representation of the water model concept is shown in Figure 2. The hydrological processes necessary to consider are summarized below.

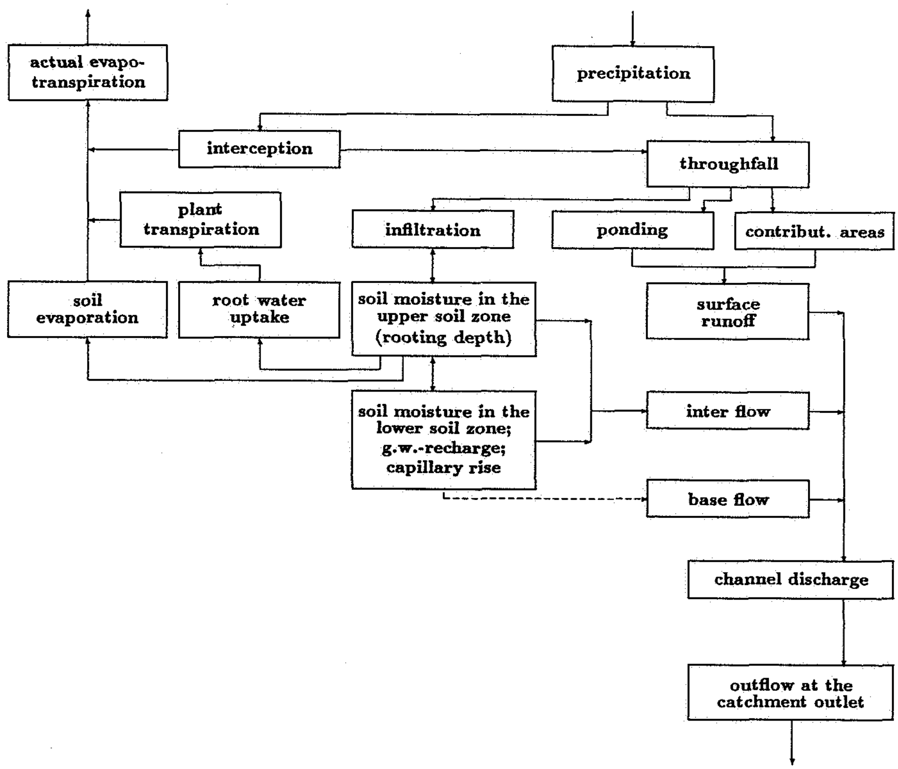


Figure 2. Concept of water movement within a catchment

## 3.1 Water input

The precipitation serves as input into the water model. In case of a plant-covered soil surface, part of the precipitation fills the interception storage. The remaining throughfall falls on the surface and is partitioned into infiltration, surface ponding and surface runoff.

## 3.2 Water movement within the soil

Infiltration is simulated according to the approach of Green and Ampt (1911) and Mein and Larson (1973), extended and modified by Plate et al. (1990). The infiltration process is simplified as vertical movement of a moisture front, the temporal effect of macropores might be considered via an increased hydraulic conductivity for a portion of the soil. During wet periods the amount of infiltration mainly influences the soil moisture content in the upper soil zone, i.e. the tilled layer and the root zone, the macropore containing soil layer respectively. Both upper and lower soil zone form the unsaturated zone, wherein the different types of water movement may yield the interflow rate at the slope bottom. According to Zuidema (1985), the fast reacting, lateral subsurface flow is induced by lateral macropores or due to the effect of a less permeable or compacted layer. This process can be one of the main sources of catchment runoff. Therefore the slope model considers this process separately. A discretization of the segment into a system of layers and columns is proposed, leading to a net of parallelogram shaped elements (Figure 3). Specific soil parameters can be assigned to each element. The lateral subsurface flow has been calculated by simple methods, e.g. from Beven (1981) by a kinematic wave or from Sloan and Moore (1984) by a kinematic storage approach. On the base of the collected field data, the practical use of these kind of approaches is to be investigated. The water movement within the micropores is caused by non-equilibrium soil potential conditions and can be computed by the Richards Equation using a computer-intensive numerical method. A simplified method, similar to the moisture front approach of the infiltration model or even more simplified as storage-type or piston-flow approach might be adapted.

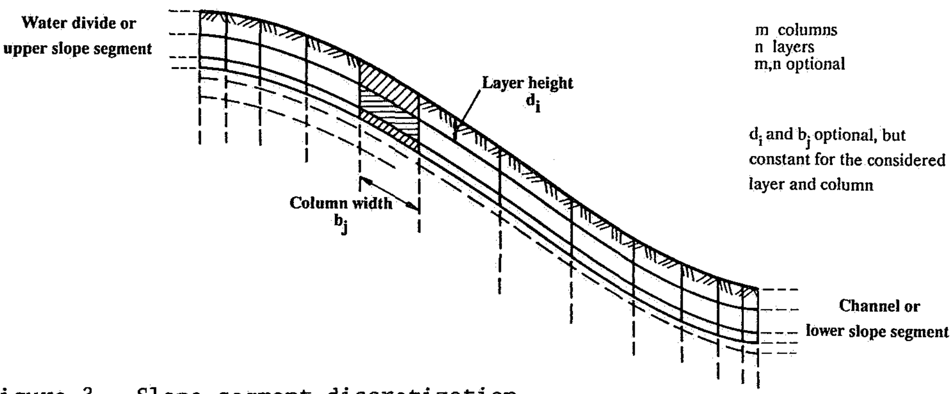


Figure 3. Slope segment discretization

## 3.3 Water movement toward the channel

Both interflow and surface runoff are the main contributors to catchment runoff during wet periods. The saturated 'contributing' areas are the main cause for surface runoff in the temperate central European climate. Surface runoff from the contributing areas will be calculated similar to the approach of Beven et al. (1984), appending that all sealed areas as agricultural roads, farm houses etc. are contributing as well.

The baseflow is of particular interest for dry period simulation. The model, though its main objective is not considering ground water drainage, may consider base flow by a simple storage-type approach.

Baseflow, interflow and surface runoff yield the channel discharge, calculated optional by the full hydrodynamic or the kinematic wave.

## 3.4 Evaporation

The actual evapotranspiration is simulated with a detailed meteorological model. A simplified calculation method like the ones of Haude-Renger or Penman-Monteith will be adapted to the conditions of the Weiherbach Catchment. The simplified methods are necessary for long simulation periods and to ensure the transferability of the model to other, less instrumented catchments.

## 4 Modelling material transport

Modelling the material migration will be based on linking the transport patterns (solution and sorption behavior etc.) of specific substance groups with the relevant hydrological process of the water cycle.
Hence the erosion model will be based on the surface runoff model. In addition to computing the eroded or deposited soil mass, the grain size distribution of the transported material has to be determined, e.g. as proposed from Plate (1987). Knowledge of grain size and clay content is required to estimate the adsorption capacity of the eroded material.
Phosphate, originated from fertilizers, tends to adsorb strongly on the soil particles it comes in contact with during infiltration. The adsorption occurs mainly at the soil surface, however if surface connected macropores are present, transfer to deeper soil may occur, too. Hence the erosion model (and the simulation of subsurface particle movement, e.g. within the field drainage) is the base of modelling phosphate transport. As an example of the transport of a specific chemical, Figure 4 shows a schematic representation of the phosphate model concept.

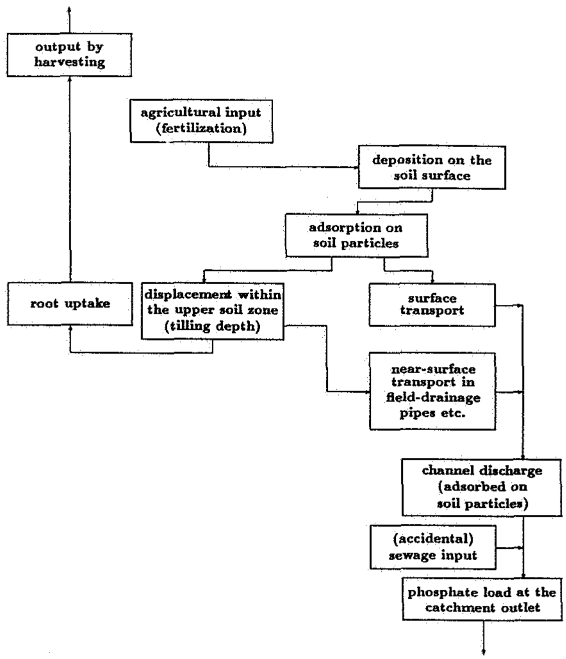


Figure 4. Concept of phosphate migration within a catchment

According to Herms and Brümmer (1984), heavy metals show similar adsorption characteristics as phosphate, i.e. erosion through surface- and inter-flow controls heavy metal transport in the catchment.

The migration characteristics of the conservative, highly soluble inorganic anions (e.g. chloride) compare to the water movement, i.e. they move within the fraction of the surface or soil water they are dissolved in (neglecting molecular diffusion and anion exclusion). Hence modelling their transport coincides with the detailed flow path and residence time describing water flow modelling.

Nitrate shows the same transport behavior as chloride. However the biolobical activities, mainly appearing in the upper soil zone and causing nitrogen immobilization, volatilization etc., can not be neglected. According to Walther (1979), the linkage of nitrate turnover in the upper soil zone and the nitrate outwash into deeper soil layers or to the drainage channels may be performed by coupling the nitrate concentrations with the relevant hydrological processes.

The transport behavior of pesticides can not be generalized. Depending on the degree of polarity of the specific pesticide, the chemical tends to get dissolved or adsorbed, see Sabatini and Austin (1990). The transformation, fate and volatilization processes are not to be neglected, but they can not be modelled in detail within this research project. Hence the pesticide model might be developed as a simple input-output approach. Only the migration of a highly adsorptive pesticide might be simulated more exact by linking its transport to the erosion processes, whereat Steenhuis et al. (1990) stresses the need of considering the possible bypass via macropores as well.

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# VERIFICATION OF DEMNIP ON DATA FROM THE HUPSELSE BEEK RESEARCH BASIN

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Abstract

DEMNIP consists of the hydrological model DEMGEN, the nitrogen soil model NITSOL, the phosphorus soil model PHOSOL and the local surface water model DIWAMO. These numerical deterministic models compute water flows, nutrient compositions of soils and loads to deeper groundwater and receiving surface water.

We have verified the models by comparing calculated with measured discharge and concentrations of N and P in the surface water of the Hupselse Beek catchment area for 1987. In general, the measurements confirm computed discharge and concentrations but indicate more dynamic behaviour than could be reproduced.

We compute with the models that application of fertilizers instead of manure might lead to higher nitrate concentrations in both surface and groundwater, caused by shortage of organic matter available for denitrification. Measurements of groundwater quality will have to confirm this assumption.

## 1 The DEMNIP model-set

The DEMNIP model-set consists of the hydrological model DEMGEN (DEMand GENenrator), the NITrogen SOil modeL NITSOL, the PHOsphorus SOil modeL PHOSOL and the DIstrict WAter MOdel DIWAMO. DEMGEN, NITSOL/PHOSOL and DIWAMO have been developed for the Ministry of Transport and Public Works.

For the hydrological analysis we use the Agro-Hydrological model DEMGEN. An overview of the DEMGEN model is given by Van Vuuren (1990). We deduced drainage functions from measured groundwater table depths of 1980-1986. NITSOL and PHOSOL compute the nutrient composition of soils and the loads to deeper groundwater and receiving surface water. The model setups of NITSOL and PHOSOL are identical. Required inputs are hydrological data on soil and groundwater flow, soil moisture content, data on nutrient inputs (manure, fertilizer, atmospheric deposition) and crop uptake (Hopstaken et al, 1987, 1988).
In local surface water systems (ditches and gullies) denitrification and sedimentation are important processes when residence times exceed 10-20 days. DIWAMO calculates concentrations in local surface water systems and the loads to (and from) regional or national systems (Ruygh and Hopstaken, 1990).

## 2 The Hupselse Beek research basin

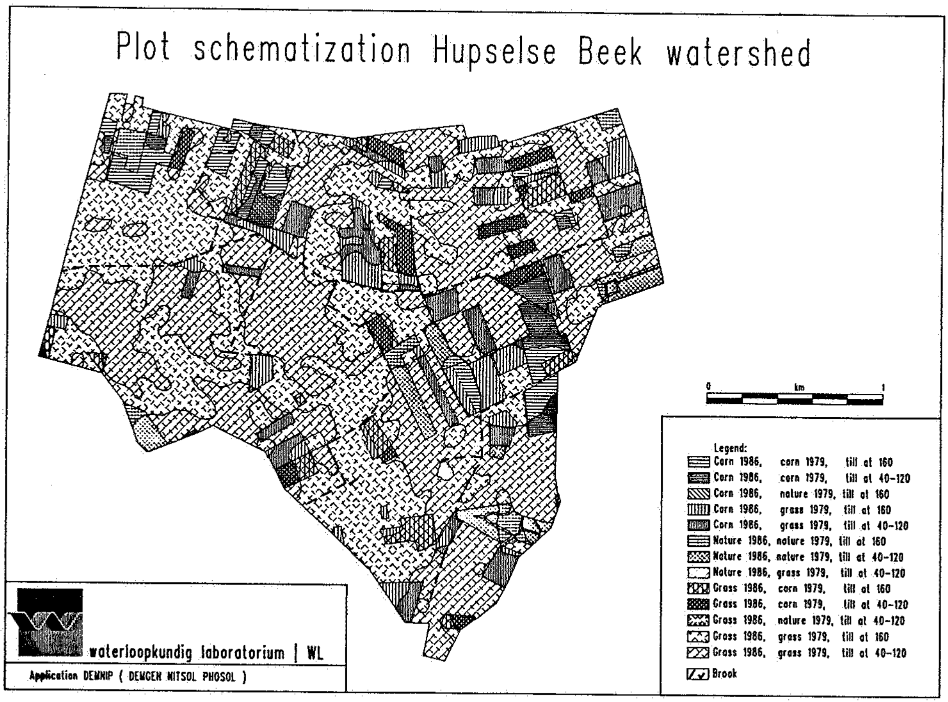
### 2.1 Brief description of the catchment area

The Hupselse Beek basin (665 ha) is situated in the eastern part of the Netherlands, near Eibergen. The presence of a shallow impermeable clay layer excludes interactions to the deeper aquifers and surrounding areas and makes the area very suitable for the verification of models. The Hupselse Beek, a rather small brook of about 4 km long, with some tributaries, is affected by local agricultural activities. Data on precipitation, evaporation, discharge and water quality have been collected by the Ministry of Transport and Public Works.

### 2.2 Schematizing the Hupselse Beek basin using a GIS

DEMNIP calculates for groups of parcels (plots) with a specific soil characteristic and land use type. The parcels ascribed to a plot may be situated anywhere within the study area; they do not have to be adjacent. We have used the Arc-Info Geographic Information System (GIS) to schematize the research area. The two most widespread soil types are used in the analysis, both sandy soils. In one type till (boulder clay) starts between 0.4 and 1.20 m. below the surface, in the other one at 1.6 m. Land use inventarisations of the Ministry of Transport and Public Works in 1979 and 1986 indicate crop rotations in the study area. Crop rotation is taken into account in the plot definition. Until 1982 we use the 1979 land use inventarisation; starting from 1983 we use the 1986 land use inventarisation.

By means of overlay techniques thirteen different plots are distinguished, as shown in Figure 1. These plots are the basic geographic units used for hydrological calculations with DEMGEN and for chemical calculations with NITSOL and PHOSOL.




| Plot | 1941-82 | 1983-87 | till at | ha | Plot | 1941-82 | 1983-87 | till at | ha |
|---|---|---|---|---|---|---|---|---|---|
| 1 | corn | corn | 160 | 22 | 7 | nature | nature | 40-120 | 18 |
| 2 | corn | corn | 40-120 | 13 | 8 | grass | nature | 40-120 | 1 |
| 3 | nature | corn | 160 | 1 | 9 | corn | grass | 160 | 20 |
| 4 | grass | corn | 160 | 35 | 10 | corn | grass | 40-120 | 22 |
| 5 | grass | corn | 40-120 | 38 | 11 | nature | grass | 40-120 | 1 |
| 6 | nature | nature | 160 | 11 | 12 | grass | grass | 160 | 226 |
| | | | | | 13 | grass | grass | 40-120 | 256 |

Figure 1. Schematization of the Hupselse Beek basin.

## 3 Input levels

As a matter of fact, insufficient data on chemical soil conditions were available to start the calculations in 1987. Initial chemical soil conditions are computed with DEMNIP by repeating metereological data of 1976-1982 six times, simulating a period of 42 years (1941-1982).
The use of manure and fertilizer in the study area was estimated by Witte (1987) for 1982 and by Van Engelenburg et al (1988) for 1987 (Table 1). With respect to the initialisation (1941-1982) we assume that the use of manure and fertilizer increased lineair to the 1982 level. The 1987 level is used in the calculations from 1983 to 1987.
According to Aalst and Van Diederen (1983) the average atmospheric deposition amounts to 46 kg N/ha.year. In nature areas leaves fall contributes 50 kg/ha N and 10 kg/ha P205 per annum (Ruygh et al, 1990). Contribution to surface water pollution from scattered buildings in the research area is estimated at 3 kg N/day and 1 kg P205/day.

Table 1. Use of manure and fertilizer on grassland and arable land in the Hupselse Beek research basin for 1982 (Witte, 1986) and for 1986 (Van Engelenburg et al, 1988)

| | 1982 Manure | | Fertilizer | | 1986 Manure | | Fertilizer | |
|---|---|---|---|---|---|---|---|---|
| | N | P205 | N | P205 | N | P205 | N | P205 |
| Grassland | 260 | 150 | 300 | 10 | 303 | 121 | 400 | 170 |
| Arable land | 1005 | 735 | 100 | 10 | 525 | 340 | 200 | 100 |

## 4 Results

The 1987 calculation with DEMNIP has been verified against data on surface water discharge and concentrations, collected by the Ministry of Transport and Public Works and the local surface water control board (Zuiveringschap Oostelijk Gelderland, ZOG).

The calibrated drainage functions have been used for simulations with DEMGEN over the period 1980 to 1988. Calculated groundwater table depths (not shown) and discharge (Fig. 2) compare well with measured values. However, peak discharges in the summer have not been calculated correctly by the model. The model overestimates discharges in the beginning of summer. Towards the end of the year the model under-estimates the discharges. These phenomena indicate that (soil) hysteresis might be an important factor even at basin area level.

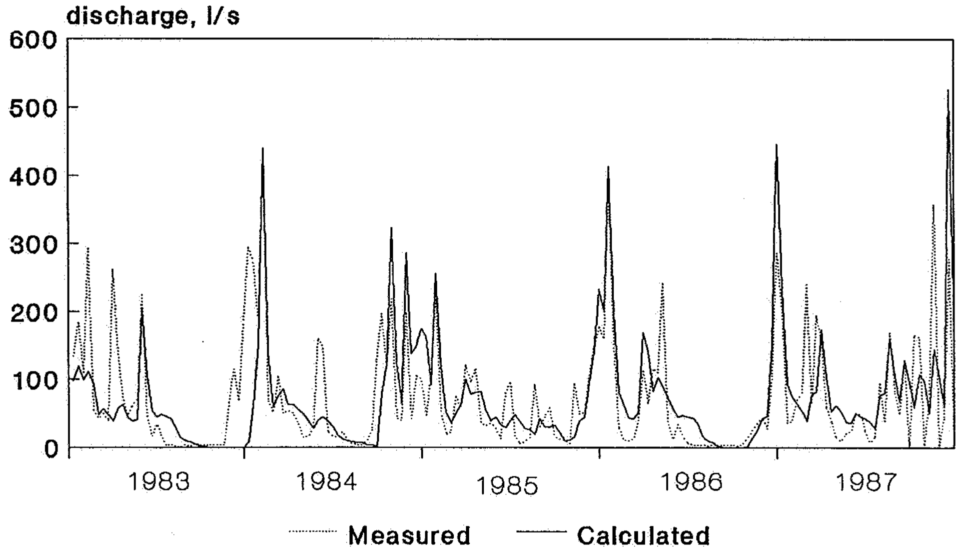
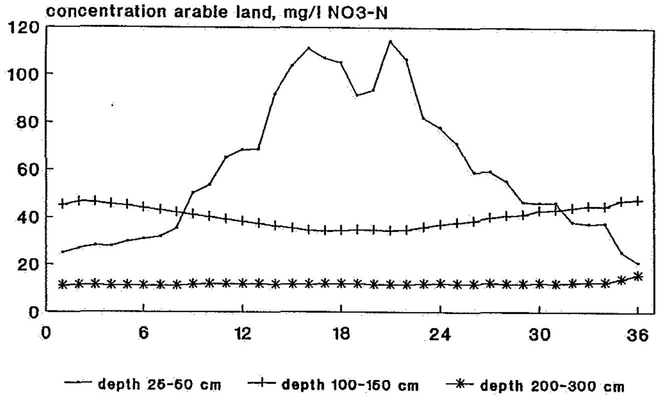



Figure 2. Calculated and measured discharge in the Hupselse Beek.

Unpublished data of the local surface water control board (ZOG) on arable land drainwater composition indicate nitrate concentrations of 50-80 mg NO3-N/l. These data confirm calculated nitrate concentrations at 75-100 cm below surface underneath arable land (Fig. 3).

With NITSOL we calculate the highest nitrate concentration (45-50 mg/l NO3-N) underneath grassland concentrations (20-30 mg/l NO3-N) are calculated in the subsoil underneath fields recently converted from grassland to corn and the lowest concentrations (10-15 mg/l NO3-N) in the subsoil underneath arable land (Fig. 3).

On arable land the application of manure provides the input of organic matter into the soil. On grassland less manure and more fertilizer is applied. Denitrification is influenced by the supply of readily decomposable organic matter (Kroeze et al, 1989). In the subsoil of grassland the low organic matter content causes a limitation of the denitrification of nitrate and consequently higher nitrate concentrations appear.



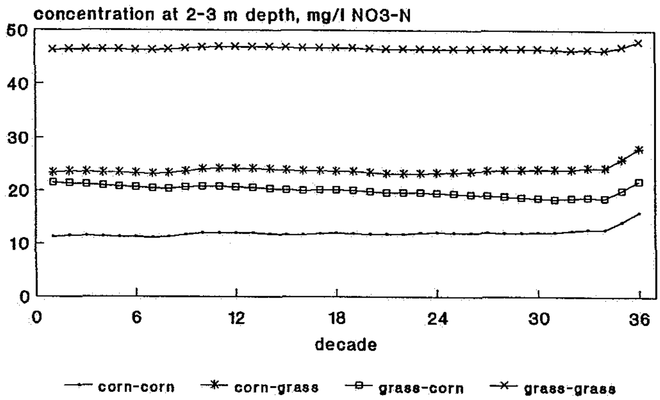




Figure 3. Calculated nitrate concentrations at arable land (upper) and in the subsoil of grassland and arable land (lower), 1987.

Calculated ortho-phosporus concentrations in the topsoil of arable land are extremely high (20-80 mg/l PO4-P, Fig. 4). At a depth of 75-100 cm concentrations are lower (2-5 mg/l PO4-P), but still above the measured arable land drainwater concentrations (0.02 mg/l PO4-P, unpubl. data ZOG). For grassland, until 1983 used as arable land (plot 9-10), high ortho-phosphorus concentrations are calculated because of the desorption of formerly adsorbed phosphorus. For arable land, before 1983 used as grassland (plot 4-5), calculated concentrations at 50-75 cm depth are still comparable to those at grassland (Fig. 4). Probably, drainwater concentrations have been collected at a parcel only recently in use as arable land and should be compared to calculated concentrations at grassland.

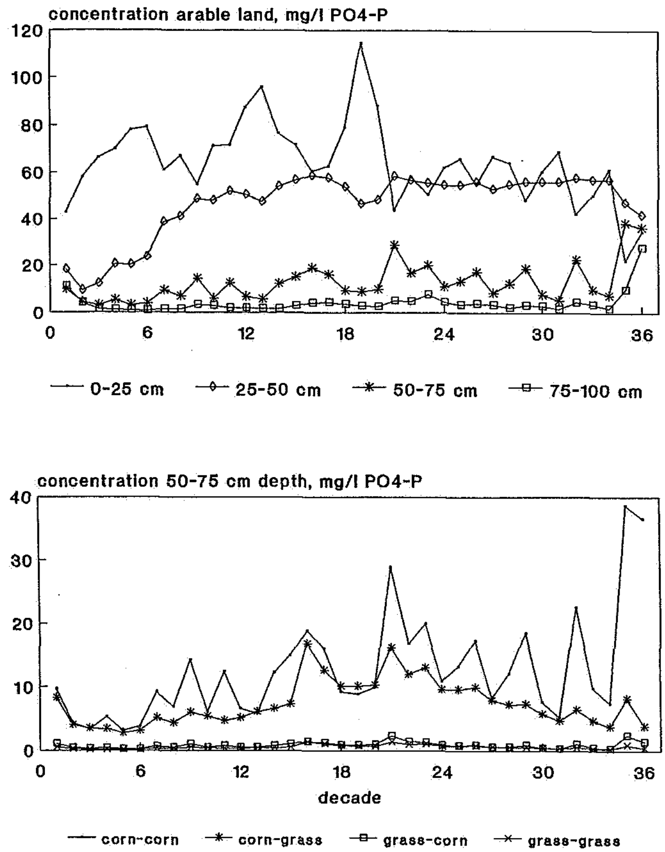



Figure 4. Calculated concentration ortho-phosphorus at arable land (upper) and in the subsoil of grassland and arable land (lower), 1987.

Calculated nitrogen concentrations in the Hupselse Beek surface water appear to be very high and dominated by nitrate (Fig. 5). The very high nitrate concentration in the surface water is caused by the contribution from the subsoil of grassland, where nitrate concentrations amount to 50 mg/l NO3-N.
Measurements indicate that most phosphorus in local surface water is adsorbed to suspended solids (Fig. 5). In groundwater, however, most phosphorus appears in dissolved form. Adsorption of ortho-phosphorus to iron and aluminium oxides in surface water is found to be important.

Calculated and measured nitrogen and phosporus concentration levels agree quite well. However, measurements indicate more variations than calculations with a timestep of 10 days could reproduce.

## 5 Conclusions

Measured discharge, nitrogen and phosphorus concentrations confirm the calculated levels but indicate more dynamics than could be predicted by means of the models (Fig. 2 and 5). However, it should be noted that we calculate decade averaged discharges and concentrations, as measurements indicate values at a certain moment. Therefore we conclude that the DEMNIP model-set is an appropiate tool to predict concentration and discharge levels of small basins.

In the subsoil of grassland higher nitrate concentrations are calculated than underneath arable land because of the lack of organic matter available for denitrification. In order to decrease nitrate concentrations in surface water, replacement of fertilizer on grassland in favour of manure might be promising.

Land use history is of great importance for the phosphorus concentrations in soil. Desorption of phosphorus accumulated in the past leads to increased ortho-phosporus concentrations, whereas recent intensive manuring only affect topsoil conditions. Even after the change of all arable land to grassland phosphorus concentrations and loads to surface water will remain high because of desorption.
All calculations should be preceded by an inventarisation of chemical soil conditions or land use history in order to estimate the initial phosphorus concentrations. At the moment we are working on this in the Hupselse Beek basin, in order to verify the DEMNIP model-set in more detail.

In surface water the adsorption of ortho-phosphorus leads to an increase in particulate phosphorus and a decrease of ortho-phosphorus concentrations. Sedimentation of particulate phosphorus does not seem to be a problem in the Hupselse Beek basin.

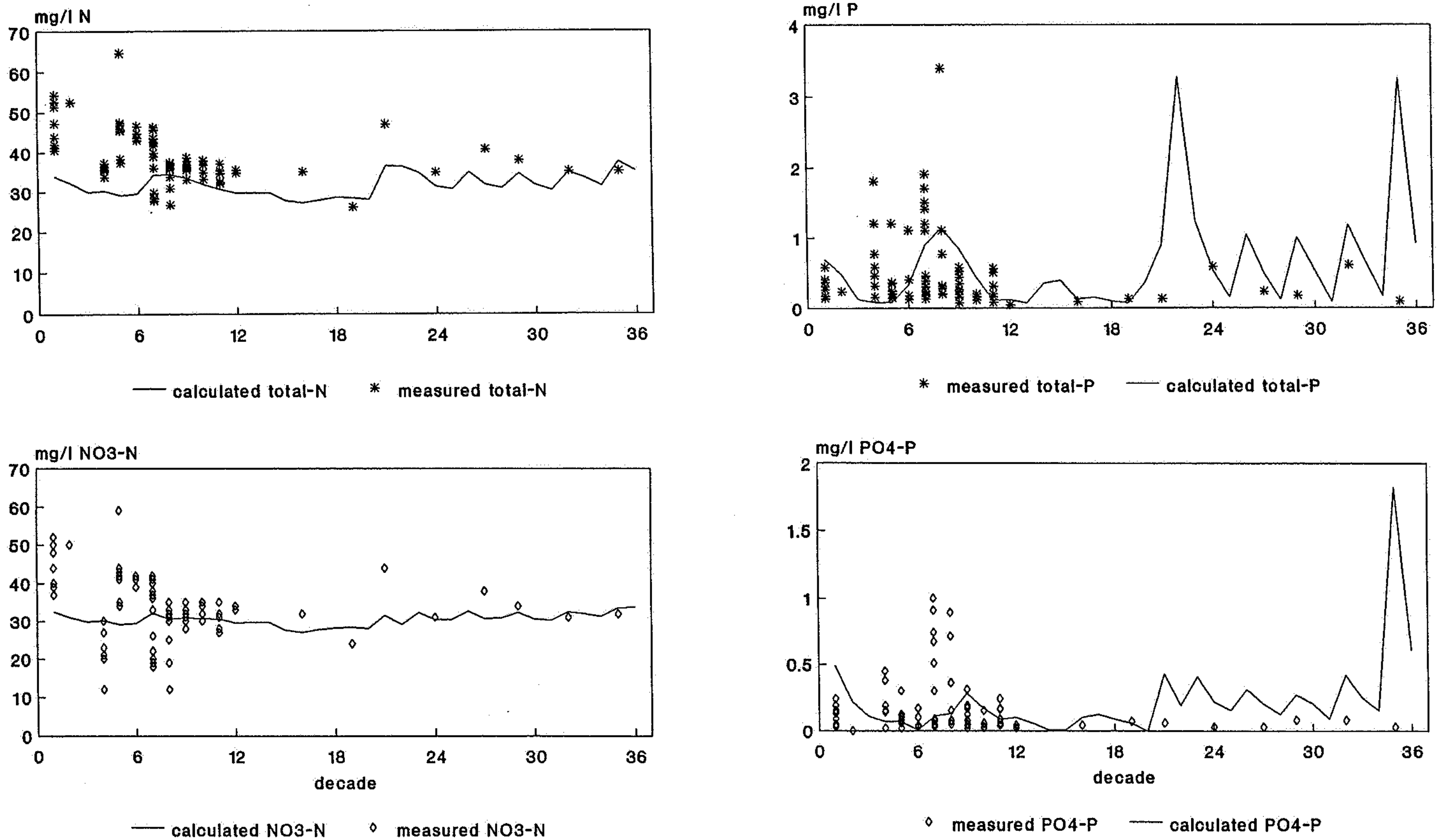



Figure 5. Measured and calculated nitrogen and nitrate (left) and phosphorus and orto-phosphorus concentrations (right), 1987.

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# CONTINUOUS MODELISATION OF CONTAMINANT TRANSPORT THROUGH THE UNSATURATED ZONE WITH A RANDOM WALK PARTICLES MODEL

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**Abstract**

A new kind of contaminant transport model through the unsaturated zone has been designed. It is a one dimensional vertical finite difference model solving Richards equation in an operational way in transient state. The scheme has been adapted specially so that the model may be used accurately with large time steps : 1/3 to 3 days (instead of 1 second commonly used) and large space gridding : 10 to 50 centimeters (instead of 1 cm commonly used). The model may then be used for real world problems simulating flows during long periods of several years (1000 time steps instead of $10^8$ !). The transport is represented by the displacement of particles with a random walk process which assures a perfect accuracy of calculations with no numerical dispersion even with large contrasts in the velocity and the permeability field. The model has been applied to a real case experimental plot made of a large layer of sand, 16 $m^2$ in area, used for geoepuration which has been monitored at Orleans during a long period and was tested with several tracer injections.

## 1 Introduction

With the rising problems of groundwater pollution by pesticides and fertilizers there is a considerable development of transport models through the unsaturated zone. It is, in fact, important to be able to predict the concentration and the time required for the pollutants to arrive in the groundwater. In addition, development of the water geo-epuration processes requires a clear analysis of the flow mechanisms through a sandy bed so as to get the best results. Lumped parameter models often enable the reproduction and, sometimes the extrapolation of observation series : Thiery and Seguin (1988), for example, simulated nitrate transport. However, to analyse the transfer mechanisms in detail and predict the influence of large modifications, it is preferable to use a physical flow model. One-dimensional vertical models in porous media have long existed ; Vauclin and Vachaud (1981) modelled flows through sandy soils in southern Tunisia for periods of fifteen days or so.

The discretization with explicit linearisation requires, however, very small calculation time steps -5 seconds in this case- associated with very small gridding -1 cm- which are not very compatible with simulations lasting decades through soil several tens of metres thick. More recently, we showed (Thiery, (1988) and (1990)) that an implicit linearisation with iterations (MERINOS model) makes it possible to obtain, economically, results which are still very precise with much larger time and space steps: 0.3 to 3 days with gridding of 5 to 20 cm on the experimental site of Mézières-les-Cléry (France). Milville (1990) also obtained good results, with the same model, with comparable time and space steps, on the Barogo basin in Burkina Faso.

Solute transport was approached, first of all, by considering a mobile phase only. Van Genuchten and Wierenga (1977), Gaudet et al. (1977), De Smedt et al. (1986) obtained better results by considering a convective-dispersive transfer of solute between a mobile water phase with simultaneous exchange of solute between the mobile and an immobile phase. Vachaud (1988) presents a review of models for solute transport in the vadose zone, showing the diversity of the models according to the hydrodynamic (steady state or transient) and more or less complex exchange scheme. However, for the study of transport in the groundwater (saturated zone), models with a " Random Walk Method" are used more and more. These present the advantage of generating no numerical dispersion, of being decoupled from the hydrodynamic calculation and of being very flexible for the introduction of complex exchange or interaction laws. Sauty et al. (1989), Kinzelbach (1988) present this method in detail. Valocchi and Quinodoz (1989) describe a new random walk method for kinetically adsorbing solute transport. The purpose of this paper is to show how the association of the MERINOS model (with implicit linearization) and a random walk method enables the effective simulation of solute transport under field conditions, economically and with no numerical dispersion even when exchange laws are taken into account. Such a scheme with particles could not, obviously, be used as such with the classic flow models with their very small (therefore very numerous) time steps since, classically, several thousands of particles must be displaced at each time step.

## 2 Hydrodynamic equation

This is Richards equation (also called "local balance equation" ) which is solved :

$$Ca \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left[ K \left( \frac{\partial h}{\partial z} + 1 \right) \right] + Q / dz \qquad (1)$$

where:

- Ca = capillary capacity
- h = pressure (negative when the soil is not saturated)
- z = vertical axis (positive upwards)
- k = hydraulic conductivity
- Q = imposed external surface flow
- t = time

The resolution of the equation at each time step gives the exchange flows between meshes, therefore the Darcy V velocities. It is, therefore, possible to write the hydrodispersive equation.

## 3 Hydrodispersive equation

The governing advection-dispersion equation (ADE) for a non reactive solute is :

$$R \cdot \frac{\partial(\theta_m . C)}{\partial t} = \frac{\partial}{\partial x}\left(\theta m \cdot D \frac{\partial C}{\partial x}\right) - V \cdot \frac{\partial C}{\partial x} - R.m.d.C - k.\theta_m\,(C-S) \qquad (2)$$

where :

- C = concentration in the mobile phase
- x = position (vertical axis z in our model)
- u = effective or pore velocity = $V/\theta_m$
- $\theta_m$ = mobile water content = $\theta - \theta_f$
- $\theta$ = water content
- $\theta_f$ = fixed or immobile water content
- R = possible retardation coefficient
- d = exponential decay factor
- k = rate coefficient $[T^{-1}]$ of solute exchange between mobile and immobile phase
- V = Darcy velocity
- S = concentration in the immobile phase
- D = Dispersion coefficient

This equation is associated with a relationship between the two phases :

$$\partial(\theta_f \cdot S) / \partial t = k \cdot \theta_m\,(C-S) \qquad (3)$$

If the exchanges are instantaneous, the S and C concentrations are in a constant ratio : $S=C.K_d$ and in the absence of decay, all that remains is to solve the equation ADE without exchanges but with a retardation factor R defined by $R = 1 + K_d \cdot \theta f / \theta_m$, where $K_d$ = concentration ratio. In steady state, when $\theta_m$ does not vary, the more classic equation is obtained :

$$R \cdot \partial C/\partial t = D \cdot \partial^2 C / \partial x^2 - u\, \partial C/\partial x - R.d.C \qquad (4)$$

## 4 Random walk resolution

The random walk method uses the movement of particles to represent the advection and dispersion phenomena. In the classical method particles are displaced with the pore velocity, u, and a gaussian random displacement with a standard deviation of $\sqrt{2D.dt}$ is added, dt being the time step. The displacement dx, therefore, writes :

$$dx = u \cdot dt + N. \sqrt{2D.dt} \qquad (5)$$

where N = standardised gaussian number.

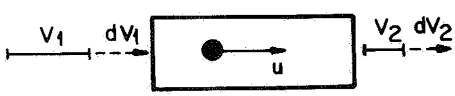
This method is, however, dangerous in non uniform flow and particularly in an unsaturated zone where small water content variations bring about very great permeability, therefore, Darcy velocity variations. The risk is to pass from a high velocity mesh through meshes with zero or almost zero velocity, or to introduce particles into stagnant water zones. To minimize these problems, the classic models generally use very small time steps which demand very expensive calculations and may result in calculation instability. We have, therefore, used a slightly different method, in which a displacement with a random component is no longer carried out but a velocity bearing a random velocity term is used. Each particle may possibly change its velocity in changing meshes and get the local velocity. It possibly stops in the presence of a zero-flux plane. A perfect conservation of the mass is thus guaranteed.

Instead of writing : $dx = u.dt + N.\sigma x$ with a standard deviation of :

$$\sigma x = \sqrt{2D.dt} \qquad (6)$$

we write : $dx = dt\,(u+N.\sigma u)$ with $\sigma u = 2D/dt$ (7)

In practice, for a given particle, only one random gaussian number is used which represents, in actual fact, the velocity field in one of its states. At the two ends of the mesh which contains the particle, the flows and therefore the V1 and V2 Darcy velocities, are known. Their respective random fluctuations are then calculated $dV1 = \theta_{m1}.N.\sigma_{u1}$ and $dV_2 = \theta_{m2}.N\,\sigma_{u2}$. The pore velocity, u, of the particle at any point in the mesh is then deduced. At each mesh change, V1 and V2 are updated but the random number N is retained. There is thus no risk of crossing immobile zones, especially if a dispersivity scheme is admitted which introduces a dispersion D equal to zero when the pore velocity is nil. Particles can therefore only reach stagnant zones by the phenomenon of molecular diffusion, which is very weak.




## 5 Decay and exchanges

According to Valocchi and Quinodoz (1989), it is also possible to simulate decay and exchanges by an efficient random walk method without numerical dispersion. Classically, the displacement (hydrodynamic) and the reactions (decay and exchanges) are decoupled. The reactions are then carried out at the beginning or at the end of time steps, which implies using very small time steps and modifying the particle mass. It is more interesting to consider the reactions - when they are linear - as a continuous time stochastic analogue. A decay or adsorption is described respectively by :

$$\partial C / \partial t = - d \cdot C \quad \text{or} \quad \partial C / \partial t = - k C \tag{8}$$

actually corresponds to a waiting time (w) of exponential statistical distribution f(w), with d or k parameters respectively before disappearance or fixation :

$$f(w) = d \cdot \exp(-d.w) \quad \text{or} \quad f(w) = k \cdot \exp(-k.w) \tag{9}$$

For the decay, for example, a random number a is used (uniform on the interval [0,1]) which is the probability F(w) of non exceeding w.

$$F(w) = 1 - \exp(-d.w) = a \tag{10}$$

where the waiting time $w = -(1/d).Ln(1-a)$

The particle is therefore displaced during the waiting time w and if the latter is less than the time step, dt, it is completely decayed (or fixed) at that moment.

## 6 Model validation

The MERINOS model was validated on 3 analytical solutions in steady state.

- injection of a mass M at initial time at the point of origin,
- injection of a constant mass flux at the origin,
- imposition of a constant concentration $C_o$ at the origin.

The analytical expressions of the concentration at the x abscissa and at time t are respectively as follows :

$$C = m / (\theta_m.\sqrt{4\pi Dt}) \cdot \exp - [(x-x_o-ut)^2/4Dt] \cdot \exp(-kt) \tag{11}$$

$$C = mf / (2\theta_m.u) \cdot [\exp[u(x-x_o)/D] \cdot \text{erfc}\, [(x-x_o-ut) / \sqrt{4Dt}] - \text{erfc}\, [(x-x_o+ut) / \sqrt{4Dt}]\,] \tag{12}$$

$$C = C_o/2 \cdot [\text{erfc}\, [(x-x_o-ut)/ \sqrt{4Dt}] + \exp [u(x-x_o)/D] \cdot \text{erfc}\, [(x-x_o+ut) /\sqrt{4Dt}]\,] \tag{13}$$

where :

m = total injected mass,

mf = mass flux (mass per time unit)

$x_o$ = injection location

$C_o$ = initial concentration

These analytical solutions have been checked with the parameters described in Table 1.

Table 1 Parameters for checking analytical solutions

| | dx | dt | $\theta_m$ | V | Sollicitation | Number Particles | Péclet number Profiles | Evolutions |
|---|---|---|---|---|---|---|---|---|
| Instantaneous | 0,05 | 4320 | 0,15 | $10^{-6}$ | 1 kg | 1000 (initial) | 58 | 120 |
| Continuous | 0,05 | 4320 | 0,15 | $10^{-6}$ | 100 kg/day | 6000 (final) | 58 | 22,5 |
| Concentration | 0,05 | 4320 | 0,15 | $10^{-9}$ | 1000 kg/m | | 6 $10^{-5}$ to $10^{-3}$ | 2,5 $10^{-3}$ to 5 $10^{-2}$ |

The Peclet numbers $P_e$ are defined by : $P_e$ = ux/D for the evolution at the position x and : $P_e$ = $u^2t/D$ for the profiles at the date t. Figure 1 shows the results obtained respectively with the model for the 3 analytical solutions. It appears that the results are very good even with a moderate number of particles (1000 to 6000). The imposition of a constant concentration is particularly hard to simulate with a particle method. The results are very good here even with almost zero Peclet numbers (less than 1/1000).

## 7 Application to the experimental geoepuration site of Orleans-la-Source

### 7.1 Measurement device

The Orleans site, described by Alamy et al. (1989 a and b), is a 1.50 metre-thick sandy layer with an area of 16 $m^2$. This layer consists of previously washed Loire sand graded at 0.2 mm. It is placed on a 0.2 m-thick gravel bed. The measuring system consists of 9 vertical tensiometers and a neutron probe tube (SOLO 25). The flow at the bottom of the basin is continuously monitored and an automatic sample-taker supplies water samples periodically for chemical analysis.

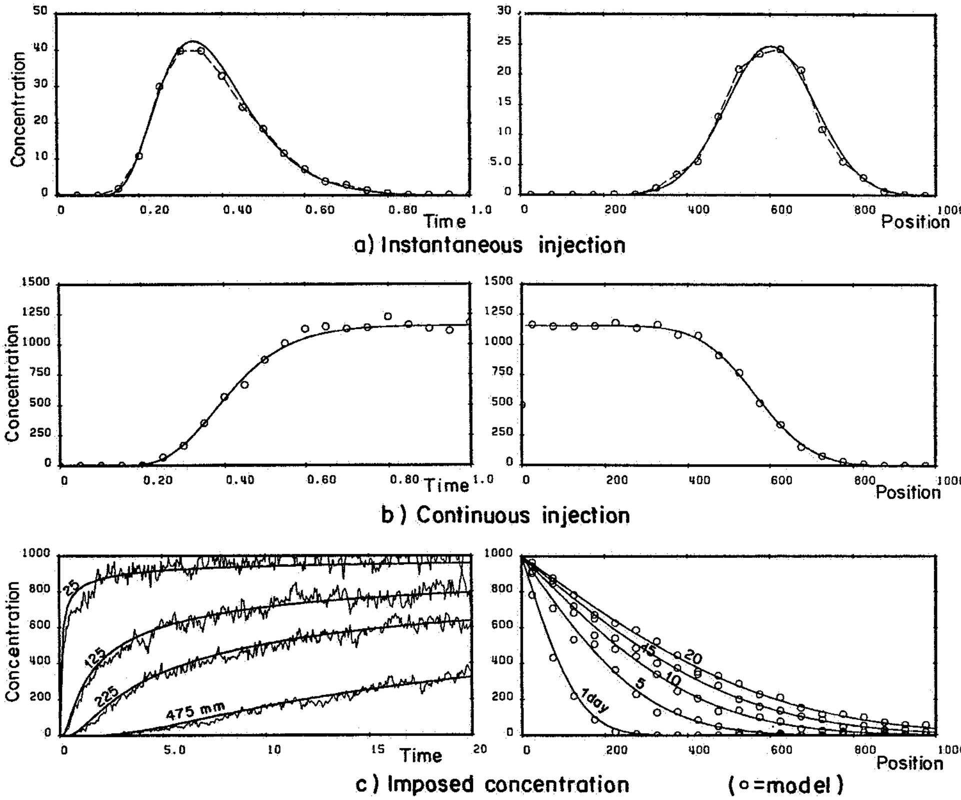



FIGURE: 1 – VALIDATION OF MERINOS MODEL WITH 3 ANALYTICAL SOLUTIONS

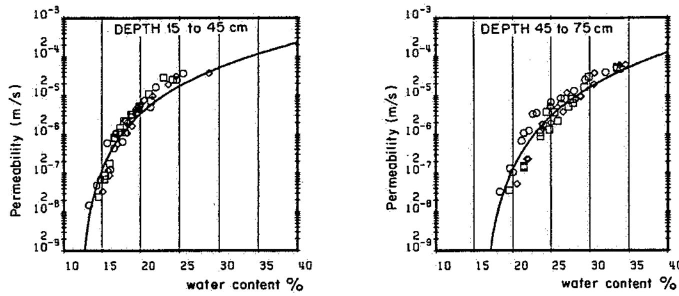



FIGURE: 2 – PERMEABILITY, WATER CONTENT RELATIONS

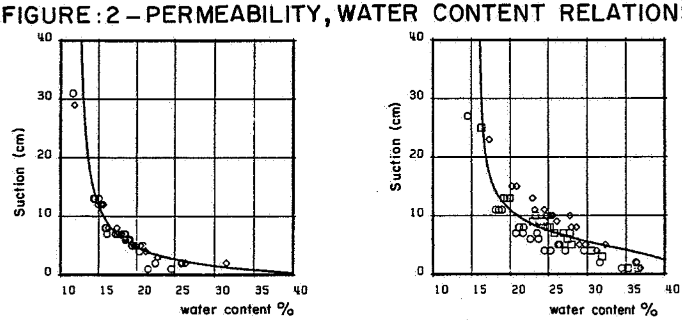



FIGURE: 3 – RETENTION CURVES

## 7.2 Test carried out

On August 17th 1989 at 13 hours, a tracer test was carried out over an area of 3 m² with 200 mm of water containing calcium (3 g/1), potassium (5.6 g/1), chlorine (9.9 g/1) and iodine (4.05 mg/1).

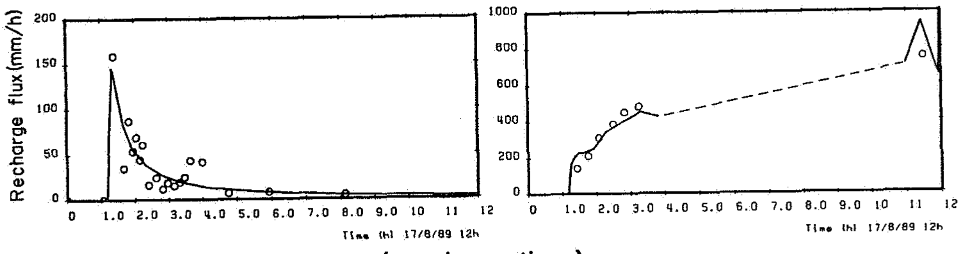
## 7.3 Hydrodynamic modelling

Interpretation of the water content and head variations during the test enabled the determination of the permeability-water content relations and the retention curves. Figures 2 and 3 show that a very good calibration is obtained with a power type permeability law and a homographic retention curve. The calibration parameters are collected up in Table 2.

Table 2 Parameters of characteristic soil laws.

| Depths (m) | Residual Water Content | Water content saturation | Permeability saturation (m/s) | Permeability expon. | Retention expon. | Suction half saturation (m) |
|---|---|---|---|---|---|---|
| 0 to 0.45 | 0.12 | 0.47 | $4.9\ 10^{-4}$ | 3.39 | 0.79 | 0.02 |
| 0.45 to 0.75 | 0.16 | 0.47 | $3.4\ 10^{-4}$ | 3.84 | 0.54 | 0.47 |
| 0.75 to 1.50 | 0.1575 | 0.47 | $5.1\ 10^{-4}$ | 5.35 | 0.65 | 0.38 |

With these parameters, the MERINOS model enabled a correct reconstitution, of the flow at the bottom of the layer, which was estimated from the storage variations measured by neutron probe (fig. 4a). The continuous flow measurements are unfortunately not exploitable.




( o =observations)

a) Bottom discharge b) Calcium concentration

FIGURE: 4 - CALIBRATION OF THE MODEL ON ORLEANS GEOEPURATION SITE

## 7.4 Hydrogeochemical modelling

Figure 4b shows that the MERINOS model with particles enables a correct reconstitution of the calcium concentration at the bottom of the layer with an immobile water content equal to the residual water content less 2 %, with a dispersivity, D/u, equal to 0.5 m and a retardation coefficient of 2.

## 8 Conclusion

The model described in this paper enables the efficient modelling of flows through porous media and solute transport. The random walk method used has the advantage of presenting no numerical dispersion and of respecting perfectly the heterogeneities while being very versatile, and allows large calculation time steps. Application to the Orleans site is only a first modelling, briefly described. It would deserve a sensitivity analysis and the modelling of the rinsings which followed the tracing 1.5 months later. However, the model made it possible to show that the very small quantity of tracers obtained at the exit are consistent considering the dispersion and retardation coefficients.

## Acknowledgements

The authors wish to thank the BRGM scientific committee for its support in the reseach project described in this paper.

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# SURFACE WATER QUALITY

# HYDROLOGIC BASIN APPROACH TO NATIONAL WATER-QUALITY ASSESSMENT IN THE UNITED STATES

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## Abstract

The U.S. Geological Survey will begin implementing a full-scale National Water-Quality Assessment (NAWQA) Program in 1990. The long-term goals of the NAWQA Program are to describe the status and trends in the quality of the Nation's surface- and ground-water resources, and to provide a sound, scientific understanding of the primary natural and human factors affecting the quality of these resources. The major activities of the assessment program are to be clustered within a set of 60 large hydrologic systems (river basins and aquifer systems), referred to as study units. Key attributes of the NAWQA Program are: (1) the use of nationally consistent study approaches, field and laboratory methods, water-quality measurements, and ancillary data measurements for all study units; (2) a commitment to long-term studies to develop a progressive understanding of water-quality conditions and trends in each study unit; and (3) the synthesis of results from the multiple study units to provide information on regional and national water-quality issues.

## 1 Introduction

In 1990, the U.S. Geological Survey will begin implementing a National Water-Quality Assessment (NAWQA) Program. The long-term goals of the NAWQA Program are to describe the status and trends in the quality of the Nation's surface- and ground-water resources, and to provide a sound, scientific understanding of the primary natural and human factors affecting the quality of these resources. The program will focus on water-quality conditions that are prevalent or extend over large areas, such as those that result from nonpoint sources of pollution or from a high density of point sources.

The design of the program is substantially different from the traditional approach of a diffuse national monitoring network. The major activities of the assessment program are clustered within a set of hydrologic systems (river basins and aquifer systems), referred to as study units. These "study units" are large, ranging in area from a few thousand to several tens of thousands of square kilometers. The program will consist of about 60 study units nationwide (Figure 1). In aggregate, the study units account for about 60 percent of the Nation's water use and represent a wide range of hydrologic settings across the country. Investigations in seven of the study units have been underway since 1986 to test and further refine the assessment concepts as part of a pilot program.

The NAWQA study-unit investigations will involve comprehensive basin studies that integrate physical, chemical, and biological measurements. Surface- and ground-water quality will be studied jointly in the program. Each study will include an analysis of available data as an early effort to provide an initial assessment of water-quality conditions.

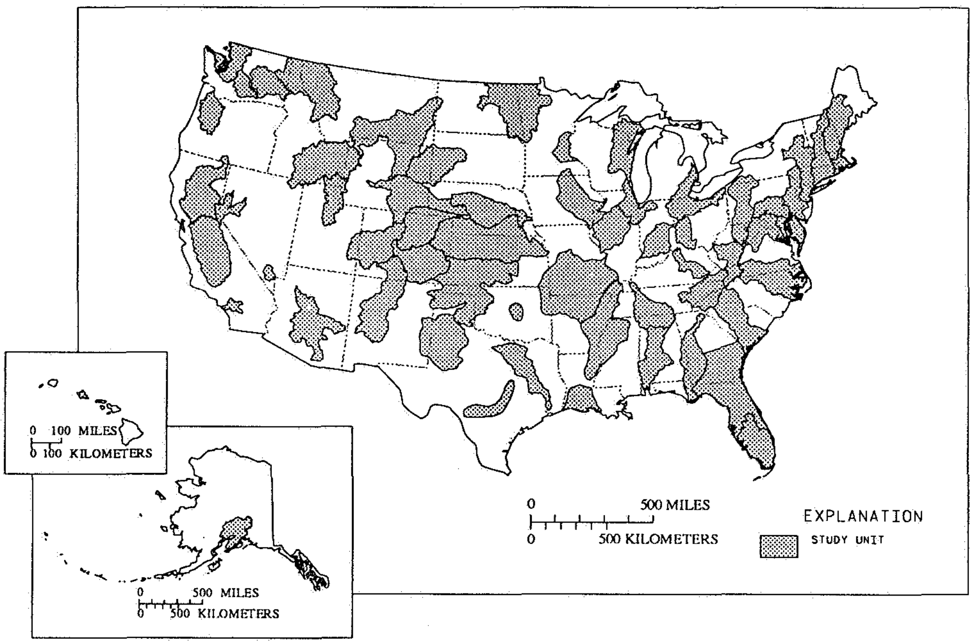


Figure 1. Location of proposed study units for a full-scale National Water-Quality Assessment Program

Unique attributes of the NAWQA Program include (1) the use of nationally consistent study approaches, field and laboratory methods, water-quality measurements, and ancillary data measurements for all study units, (2) the development of a progressive understanding of water-quality conditions and trends in each study unit through long-term studies, and (3) synthesis of results from the study units to provide information on regional and national water-quality issues. This paper will briefly describe these three attributes. For a more complete description of the program, the reader is referred to the report by Hirsch, et al. (1988).

## 2 National Consistency

A national framework has been established to ensure consistency among the study-unit investigations. Key attributes of this framework are as follows:

a) Each study-unit investigation will follow a prescribed set of study approaches that represent a balance between the need to be responsive to the unique characteristics of each study unit and the need to contribute toward the national goals of the program. The approaches will include both regionwide surveys and more localized studies of key and(or) representative areas. Surface-water sampling approaches include fixed-station sampling at selected key locations, periodic regionwide synoptic surveys of chemical and biological measurements, and studies of selected stream reaches. Ground-water sampling approaches include broad survey sampling of major hydrogeologic settings and targeted sampling of selected areas. Much of the targeted sampling will involve transects of wells in representative settings.

b) A prescribed set of protocols for sample collection, sample handling, laboratory analysis, ancillary data collection, and quality assurance will be followed. Examples of these protocols for the pilot program are the reports by Mattraw, et al. (1989) and Hardy, et al. (1989).

c) Sample analyses for all study units will include a national list of target variables consisting of a common set of physical measurements, biological measurements, inorganic constituents, and organic compounds. Within each study unit, additional constituents will be selected to address regional or local water-quality issues not addressed by the national list. In addition to chemical analyses of tissues, the biological measurements will include measurements of fecal contamination and ecological surveys to examine the characteristics of invertebrate and fish communities in relation to the physical and chemical characteristics of streams.

d) Consistent records of ancillary information on well and aquifer characteristics and land use and other measures of human activity will be maintained. In addition, records will be maintained on the criteria used to select individual sites for the different sampling activities. Experience has shown that a lack of consistent ancillary information and a lack of records on why individual sites were selected for sampling are key stumbling blocks in attempts to aggregate existing data from individual studies to provide information useful at broader scales.

e) Data will be stored in national data files, where they will be readily available to the user community upon request.

## 3 Long-term Studies

The NAWQA Program is designed to be a long-term program continued over decades. The long-term nature of the program is required to reveal the presence of important, slowly evolving trends, but also is important in fostering a progressive understanding of water quality in the study areas.

To make the program manageable, the assessment activities in each of the 60 study units will be done on a rotational rather than a continuous basis. Only 20 of the study units will be studied in detail at a given time. For each study unit, 3- to 5-year periods of intensive data collection and analysis will be alternated with slightly longer periods during which the assessment activities will be less intensive.

The initial intensive phase in each study unit will lead to a characterization of present water-quality conditions and will provide an understanding of the factors influencing these conditions. Subsequent periods of intensive data collection and analysis will focus on the changes in water-quality conditions. To avoid the major historical pitfall of long-term monitoring--a lack of timely interpretation of the data--emphasis will be given to writing an interpretive report after each set of repetitive sampling activities.

The program will evolve with time as a result of changes in knowledge of hydrology, improved methods of measurement, and changes in the types of contaminants of concern. However, substantial emphasis will be placed on repetition of measurements and on the careful documentation of data-collection sites and the methods of data collection and analysis.

## 4 Regional and National Synthesis

Providing meaningful information at the national scale is the major scientific challenge of the program. The problem is complex, because there is no "national water quality" in any meaningful sense of the term. Much of the motivation for the design of the program is based on the observation that the Nation's water resources are an aggregation of numerous hydrologic systems, each of which has its own set of hydrologic, chemical, and biological characteristics and each of which responds to natural and human stress differently.

The national issues faced by NAWQA are in essence common problems that manifest themselves differently among the Nation's diverse hydrologic systems. The NAWQA Program is not intended to produce water-quality maps of the United States, nor is it conducting a statistical survey of the environment. Rather, the intent is to emphasize the development of a greater understanding of major factors affecting water quality in different parts of the country. Considerable emphasis is placed on opportunities in comparative hydrology to identify and explain commonalities and differences in water quality found among the study units.

Thus, local and study-unit-wide activities are intended to form a foundation for regional (multistudy unit) and national scale syntheses. Four primary scales of inquiry exist within the program, as summarized in Figure 2. These different scales of activity are shown sequentially. In practice, the different scales will be studied in tandem with considerable feedback among them as the program evolves.

Regional (multistudy unit) syntheses of information from among selected study units will provide an important intermediate step toward national assessment. Some of the regional syntheses will focus on large hydrologic regions, such as one or more of the 21 Water Resources Regions of the United States (Seaber, et al., 1986) or the High Plains aquifer system in the central part of the country. Many of the regional syntheses, however, will represent geographic areas defined by the specific issue under study. For example, interpretations for a selected suite of pesticides will focus on study units where the pesticides are most widely used. On the other hand, a study of selected constituents in shallow alluvial aquifers will draw on results from study units having that particular hydrologic setting. By including a large number of study units and a large part of the United States, the program ensures that such comparisons are possible for many water-quality issues and hydrologic settings.

For the national scale shown in Figure 2, a series of reports will be produced by the program largely from the synthesis of

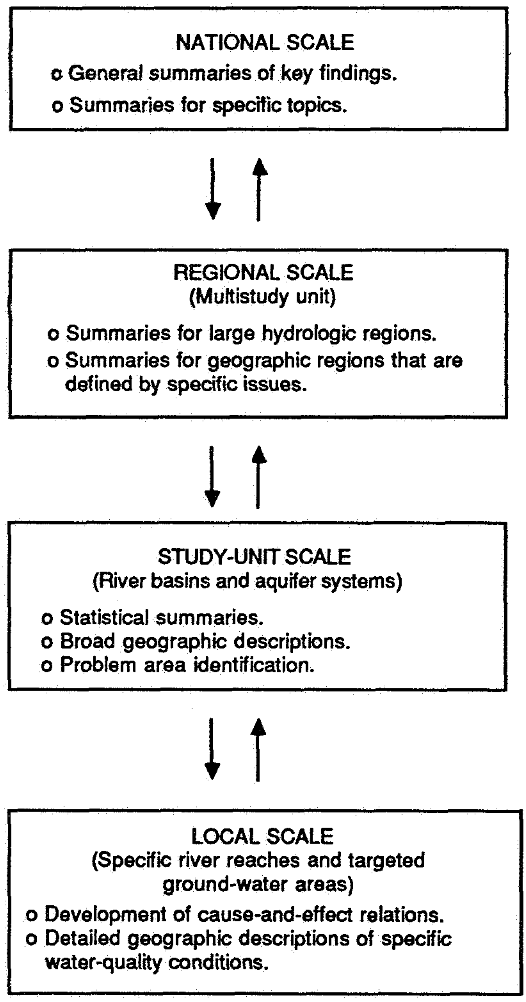


Figure 2. Information provided at different scales by the National Water-Quality Assessment Program

regional findings. Some examples of the types of national issues for which the NAWQA Program would contribute information include:

- What is the extent of surface- and ground-water contamination across the Nation from different types of nonpoint sources?

- What are the relations between pesticide application rates, soils, and hydrogeologic factors and the occurrence of pesticides in surface and ground water nationwide?
- How reliable are various measures of ground-water vulnerability to contamination? and
- Where and under what conditions does surface-water quality have a major effect on ground-water quality and vice versa?

The NAWQA Program provides an infrastructure to examine these questions in a host of different settings nationwide.

The results will be summarized in a continuing series of topical national reports produced by the program. In addition, every 3 to 5 years, a summary report is planned to present statistical summaries of the status and trends in water quality within the study units together with regional and national summaries of key findings.

## 5 Summary

Water-quality monitoring and assessment programs generally have not considered the use of multiple scales in their designs. Yet, the scales used within any program will have a controlling influence on the issues that can be addressed and the level of understanding that can be provided by the program.

The issue of scales is central to the NAWQA concept. The principal challenge in designing and implementing the program is to provide the proper balance among scales and to facilitate a smooth flow of consistent and long-term information among local, study-unit, regional, and national scale studies.

The relevance of the program at the national scale rests primarily on its ability to provide key findings from comparative studies conducted in a large set of study units and in a wide range of hydrologic settings nationwide. A long-term commitment to investigative activities in the selected study units is a key attribute of the program, not only to examine trends, but also to build a progressive understanding of water quality in each study unit with time. Improved understanding will be achieved through analysis and interpretation of long-term data sets on water quality in concert with carefully compiled data on changes in the land use and physical hydrology of the study units.

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# HYDROLOGICAL PROCESSES IN THE SLAPTON CATCHMENTS AND THEIR RELATIONSHIP TO SEDIMENT AND SOLUTE LOSSES

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Abstract

Slapton Ley is the largest natural lake in south west England. Since the 1960s, there has been much more concern that the Ley is becoming increasingly eutrophic. From 1969 a monitoring programme has been maintained to quantify inputs into the lake, and to link runoff processes to the loss of sediment and nutrients from the catchment.

## 1 Site description

Slapton Ley is a coastal lake, 10 km south west of Dartmouth, Devon (UK National Grid Reference SX 825479). It is divided into two parts: the Higher Ley (39 ha) is mainly reed marsh; the Lower Ley (77 ha) is 84% open water (Van Vlymen, 1979). The lake is a sink for sediment and solute inputs from the surrounding catchment which is an area of mixed farmland with a relatively small (c.2000), dispersed population.

The catchment of Slapton Ley (46 km2) is subdivided into four subcatchments (Table 1); the gauged areas of each together comprise 81% of the total. Ungauged areas plus minor drainage basins which drain directly into the Ley account for the remaining 19%. The area is underlain by impermeable slates and shales of Lower Devonian age. The soils are freely draining, acid, nutrient-poor, silty clay loam soils, up to 3 m deep in valley bottoms, though much shallower on steep slopes.

Table 1. Characteristics of the 4 catchments draining into Slapton Ley. Based on Van Vlyman (1979), Heathwaite et al (1989), and Johnes and O'Sullivan (1989). All losses expressed in kg $ha^{-1}$ $a^{-1}$.

| | Gara | Slapton Wood | Start | Stokeley Barton |
|---|---|---|---|---|
| Gauged area (km2) | 23.62 | 0.93 | 10.79 | 1.53 |
| % grassland | 81.2 | 32.1 | 52.6 | 28.8 |
| % arable | 11.9 | 36.1 | 34.3 | 66.6 |
| Annual runoff (mm) | 781 | 463 | 535 | 294 |
| Measured loss of: | | | | |
| Nitrate | 71.03 | 69.17 | 71.27 | 41.89 |
| Ammonium | 0.92 | 0.14 | 0.38 | 0.27 |
| Phosphate | 0.43 | 0.22 | 0.51 | 0.47 |
| Suspended sediment | 218.48 | 67.76 | 104.36 | 47.83 |
| Predicted loss of: | | | | |
| Total N | 32.53 | 17.05 | 35.62 | 41.15 |
| Total P | 0.55 | 0.26 | 0.58 | 0.61 |

Catchment topography consists of wide plateaux of low gradient dissected by narrow deep valleys (maximum slope angle 25°). The landrises to over 200 m altitude in the northern part of the basin, which is drained by the River Gara; land use in this area is dominated by permanent pasture and temporary grass with the lowest proportion of arable land. Further south, lower altitudes allow the development of mixed farming with one third of the area under arable cultivation (Johnes and O'Sullivan, 1989).

Mean annual rainfall (1961-88) at the Slapton Ley Field Centre is 1039 mm; Van Vlymen (1979) estimates that the value for the entire catchment may be 15-20% higher. Stream discharge leaving the two smaller basins (Table 1) is measured using thin plate V-notch weirs; rated sections are used on the two larger rivers. Mean annual runoff for the entire catchment is 639 mm (Van Vlymen, 1979). The area has a mean annual temperature of 10.5° C.

## 2 Hydrological processes

The combination of impermeable bedrock, permeable soil, high rainfall and steep slopes, promotes subsurface runoff. Infiltration capacity is high for woodland soils (180 mm $hr^{-1}$; Burt et al., 1983), where fields are freshly ploughed (50 mm $hr^{-1}$), or in lightly grazed grassland (30-40 mm $hr^{-1}$). However, the soils are easily compacted by farm machinery, with infiltration capacity falling to 4 mm $hr^{-1}$, and by animals, infiltration capacity falling to below 1 mm $hr^{-1}$ where fields are severely overgrazed (Heathwaite et al., 1990 a). Observations of rill erosion show that widespread infiltration-excess overland flow can occur in the Slapton catchments when soil and rainfall conditions are suitable. Tracks and roads may also be an important source of both storm runoff and sediment. Even so, only about 1% of total runoff is quickflow, and some of this may be derived from sources other than infiltration-excess overland flow. Although storm runoff production in the area conforms closely to Hewlett's Variable Source Area model, source areas producing saturation overland flow are restricted to the base of hillslope hollows; most runoff is subsurface in origin. Burt and Butcher (1985) showed that a large volume of this runoff occurs during delayed hydrographs which peak several days after rainfall; such hydrographs occur about eight times every winter. Only in catchments where conditions are favourable for the generation of subsurface runoff are such hydrographs recorded. In summer, when soil moisture deficits are high, only quickflow hydrographs occur, indicating that no lateral subsurface flow occurs through the soil at such times. Burt and Butcher (1985) describe the soil moisture variations during delayed hydrographs. In winter after significant rainfall (above 10 mm) a saturated layer develops at the base of the soil profile. The largest delayed hydrographs occur when hydrological connectivity is established between the extensive saturation on the plateau areas and the stream channel. In smaller events, only valley side slopes contribute to the runoff response. In effect, a variable source area for subsurface, as well as for surface runoff, may be identified. Coles and Trudgill (1985) have identified a pedal infiltration capacity of 2.5 mm $hr^{-1}$, with inter-pedal preferential flow occurring at higher rainfall intensities. This may account for rapid saturation at the base of the soil profile very soon after rainfall.

## 3 Sediment and solute production

In order to quantify the production of surface runoff and suspended sediment from different land uses, a series of plot experiments were conducted (Heathwaite et al., 1990 a,b). Surface runoff from overgrazed permanent grassland was double that from lightly grazed areas, and at least twelve times that from ungrazed areas. Additionally, a lack of vegetation due to severe poaching led to an increase in loss of suspended sediment, total nitrogen and total phosphorus in surface runoff. Over 90% of the total nitrogen delivered was in inorganic $NH_4$-N form, whereas for phosphorus, over 80% was in organic form. It is likely that phosphorus losses from farmland are largely derived from surface runoff (see Section 5 below).

Studies of subsurface runoff have been conducted at both plot and hillslope scale. Plot experiments have established that preferential flow of soil water down structural pathways can be responsible for the rapid movement of a proportion of surface applied nitrate fertiliser to soil drainage waters. Burt et al. (1983) found that delayed subsurface hydrographs are strongly associated with nitrate leaching since both flow and concentration are high at such times. Hillslope hollows are major point sources of discharge and nitrate, but all slopes are significant source of non-point subsurface inputs (Burt and Arkell, 1987).

## 4 Catchment budgets

The major loss of nitrate occurs in winter when both discharge and nitrate concentration are at their highest (Table 2). In the 1984 water year (beginning 1 October 1983), 79% of the total nitrate load was exported from the basin in the three months, December to February inclusive. Since the period described on Table 2 covers two winters, it is of some interest to compare nitrate losses. The 1983/84 winter was relatively dry. The next winter wetter and followed a summer drought;

nitrate concentrations and loads were both very much higher as a result, a feature which was also noted at the end of the 1975-76 drought in many British catchments, including those draining into Slapton Ley (Burt et al., 1988). Given a mean annual nitrate load of 40 kg $ha^{-1}$ and an inorganic fertiliser application (in 1986) of 127 kg $ha^{-1}$, the mean annual loss of nitrate from the Slapton Wood catchment is equivalent to about 30% of the annual inorganic fertiliser application; in wet years the proportion may be considerably higher.

Table 2. Monthly totals of discharge and nitrate load for the Slapton Wood catchment for the period October 1983 to April 1985 (From Burt, 1988).

| Month | Rainfall (mm) | Discharge (mm) | Nitrate conc. ($mg.l^{-1}$ $NO_3$-N) | Nitrate load (kg) |
|---|---|---|---|---|
| 10/1983 | 75 | 12.0 | 6.37 | 71.86 |
| 11/1983 | 69 | 12.6 | 7.00 | 82.25 |
| 12/1983 | 117 | 83.0 | 7.75 | 604.72 |
| 01/1984 | 243 | 184.0 | 7.79 | 1346.74 |
| 02/1984 | 70 | 104.0 | 9.15 | 894.58 |
| 03/1984 | 65 | 29.0 | 8.29 | 225.71 |
| 04/1984 | 8 | 24.7 | 7.05 | 163.44 |
| 05/1984 | 62 | 16.2 | 6.62 | 100.63 |
| 06/1984 | 9 | 8.4 | 6.19 | 48.88 |
| 07/1984 | 34 | 5.5 | 5.86 | 130.28 |
| 08/1984 | 54 | 5.3 | 6.01 | 29.83 |
| 09/1984 | 89 | 4.1 | 7.17 | 27.95 |
| 10/1984 | 123 | 10.4 | 6.65 | 65.21 |
| 11/1984 | 203 | 95.7 | 9.72 | 874.12 |
| 12/1984 | 106 | 100.8 | 10.26 | 971.38 |
| 01/1985 | 114 | 114.4 | 9.81 | 1055.00 |
| 02/1985 | 54 | 99.8 | 9.99 | 937.86 |
| 03/1985 | 92 | 28.7 | 9.18 | 247.26 |
| 04/1985 | 65 | 70.7 | 8.62 | 572.11 |

Heathwaite et al. (1989) have produced load estimates (inorganic only) for all four catchments for the period April 1987 to March 1988 (Table 1). All catchments, except Stokeley Barton, produced high nitrate losses which are, for reasons discussed below, at least double those reported by Troake et al. (1976). Phosphate losses increase towards the south of the area; this may reflect the higher percentage of root crops grown in that area.

## 5 Long-term changes

Burt et al. (1988) analysed changes in stream nitrate levels in the Slapton Wood catchment for the period 1970-1985. They identified a sustained increase in nitrate concentration of about 0.2 $mg.l^{-1}$ $NO_3$-N $ha^{-1}$. Farming in the basin has become ever more intensive during this period, with increased fertiliser use, more frequent ploughing of grassland, more intensive stocking of grassland, and a higher acreage of arable crops. Nitrate concentration in a given year was not significantly correlated either with rainfall or runoff in that year. However, antecedent conditions were found to be important as concentrations tend to be higher in the year following a drought, and vice versa. Annual nitrate loads are significantly dependent on annual runoff: high nitrate losses are mainly a reflection of high rainfall, although the continuing rise in nitrate concentration has weak indirect effect on nitrate loads too (Burt et al., 1988).

Johnes and O'Sullivan (1989) have calculated nitrogen and phosphorus inputs to Slapton Ley using an export coefficient model. Predicted losses from farmland were calculated to be 32.48 kg $ha^{-1}$ total N and 0.54 kg $ha^{-1}$ total P of which 12.3 kg $ha^{-1}$ N and 0.1 kg $ha^{-1}$ P were in inorganic form. Since the predicted loss of total N is somewhat less than observed losses of inorganic N (Table 1), this suggests that much of the loss of organic N from farmland must be converted into inorganic forms during transport, if the model is correct. Estimated losses of nitrogen and phosphorus from sewage are not, in absolute terms, very great. However, whilst sewage may generate only about 5% of the total nitrogen exported from the catchment, it may supply nearly 50% of the total phosphorus. Johnes and O'Sullivan argue that, even if sewage phosphorus could be reduced, Slapton Ley would still be hypereutrophic and that to reduce nutrient loads any further, some attention would need to be paid to losses from agricultural land. Current research is seeking to compare measured and predicted loads, and to use historical records of land use and livestock numbers as a basis for predicting N and P loads pre-1970.

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# MOVEMENT AND TRANSFORMATION IN THE SOIL AND LEACHING TO SURFACE WATER OF PESTICIDES APPLIED TO FLOWER-BULB FIELDS

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Abstract

Transport, transformation and leaching of three pesticides (1,3-dichloropropene, metamitron and maneb/zineb) were studied on an experimental field with a loamy sandy soil. To control the leaching of the three pesticides, water samples were taken on a discharge-proportional basis. The first results showed that 1,3 dichloropropene at a content of 10-15 mg/kg in combination with high soil temperatures, transforms quickly. Some leaching due to rainfall occurred. However, this was less than 0.001% of the initially fumigated 1,3-dichloropropene.

## 1 Introduction

Increasing areas of the IJsselmeerpolders are reserved for flower bulb cultivation. Pesticides are essential for this cultivation and are normally applied in considerable amounts. The future use of pesticides in the IJsselmeerpolders is a source of great concern, because it might degrade the soil and ground water systems. In order to formulate management and design criteria, a model is developed to simulate the leaching of pesticides to ground and surface water. Leaching of a pesticide depends on its chemical behaviour in the soil, the way it is applied, soil and soil water characteristics and climate conditions. As the knowledge of the different aspects is limited, a research project was started.

To gain more knowledge and validate a future transport model a field experiment was introduced. The field experiment includes three different pesticides and started in september 1989 with the injection of the fumigant 1,3-dichloropropene. In this paper the measurement strategies and some first results of the experiment are presented.

## 2 Material and methods

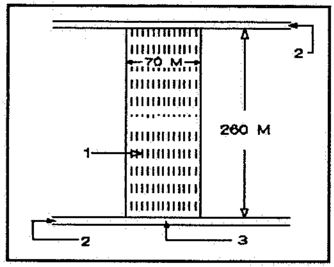
The movement and transformation of pesticides in the soil and the leaching to the surface water depend mainly on the type of pesticide and the soil characteristics. For this a selection had to be made among the vast group of pesticides, used in the flower bulb cultivation. The soil characteristics of the experimental field are representive of the soil characteristics of those soils on which flower bulbs are grown in the IJsselmeer-polders.

### 2.1 Description of the experimental field

The field experiments are conducted on an experimental field (70m * 260m) in the North-East polder nearby the village of Creil. In this part of the polder flower-bulbs are grown around every six years. Tulips were planted on the experimental field in October. The soils in the region consist of an approximately 0.9 m thick surface layer of Almere and Zuiderzee deposits (Zuur, 1951), underlain by a 0.3 m thick peat layer of low permeability. The loamy sandy soils of the experimental field are

Table 1. Composition of the soil.

| Depth (M) | Mass fraction (%) Organic matter | Clay (< 2 um) | Calcium carbonate |
|---|---|---|---|
| 0-0.3 | 1.9 | 5.2 | 4.9 |
| 0.3-0.5 | 0.4 | 3.1 | 4.9 |
| 0.5-0.7 | 1.3 | 8.9 | 4.5 |
| 0.7-0.9 | 1.1 | 4.1 | 7.0 |




1. Tile drains (drain spacing 4 m)
2. Ditch
3. Automatic water sampler and tank

Figure 1. Experimental field "De Waag".

comparable with the soils of the new polder. The characteristics of the soil are given in Table 1. The tile drains are situated at 0.9 m depth, just above the peat layer with a drain spacing of 4 m. On both short sides of the field the drain discharges into ditches (Fig. 1). From the drainwater discharge and the convexity of the groundwater table, the hydraulic conductivity was calculated at 0.4 $m.d^{-1}$.

## 2.2 Application of pesticides

Research takes place on the following pesticides :

1. (E) and (Z) 1,3-dichloropropene, a fumigant. It plays a major part in the protection of flower-bulb crops against nematodes and fungi, which cause root rot and transmission of virus diseases. About 150 kg/ha of 1,3-dichloropropene were injected at a depth of 0.2 m on 6 September 1989.
2. Metamitron, a herbicide. Metamitron is used to control germination and grass weeds in flower-bulbs. Approximately 2.5 kg/ha of metamitron was sprayed on the experimental field on 22 February 1990.
3. Maneb/Zineb, a fungicide and its degradation product ETU (ethylene-thiourea). Maneb/Zineb is used for the control of a variety of fungus diseases. The transformation of maneb/zineb happens very quickly. Its degradation product, ETU is known as a weakly sorbed compound. Application of Maneb/Zineb started at 28 February 1990 and was repeated weakly until the end of May.

Bromide is not adsorbed by sandy soils, so its movement can be tested in the model as a non-sorbing compound. For this reason, bromide is used as a tracer and applicated to the experimental field on 22 February 1990 together with metamitron. The distributed quantity of bromide amounted to 90 $kg.ha^{-1}$.

## 2.3 Measurements and samples

### 2.3.1 Measurements at intervals.

The degradation of pesticides depends among others on the soil temperatures and soil water content. Therefore soil temperatures are registered every hour at 4 different depths (0.2, 0.4, 0.6 and 0.8 m). Soil water content is determined with the help of tensiometers (Jet Fill), which were placed in duplicate at four different depths (0.2, 0.4, 0.6 and 0.8m) and registered three times a week. The hydraulic head of the groundwater below and above the peat layer is recorded every hour (Campbell recorder). From these figures the possible seepage (or downward seepage) can be calculated.

### 2.3.2 Drainwater discharge measurements and sampling.

Drainwater of four drains is collected using a tank which is partially sunken into the bottom of the ditch. The drain outlets are connected with the tank by plastic tubes. Samples are collected on a discharge proportional base. Whenever the water level reaches a floating contact, a water sample is pumped automatically from the tank into an automatic water sampler (PB MOS Edmund Bühler). In this way a water sample is taken every 0.4 mm of drain discharge. The entire system is controlled with a Campbell recorder, which in addition registers the volume of the drain discharges.

### 2.3.3. Soil sampling.

For 1,3-dichloropropene, metamitron and bromide soil sampling took place one week before application and 1, 14 and 48 days after application. Maneb/zineb and ETU were sampled one week before and every 30 days up to 120 days after the first application. The experimental field was divided into 5 different sections. Each section consists of five plots. From each plot four soil samples are taken every 0.225 m up to a depth of 0.90 m. The different samples of the same depth, section and time are mixed. This procedure resulted into twenty mixed soil samples for each chemical at each sampling time.

### 2.3.4. Adsorption and transformation experiments in the laboratory.

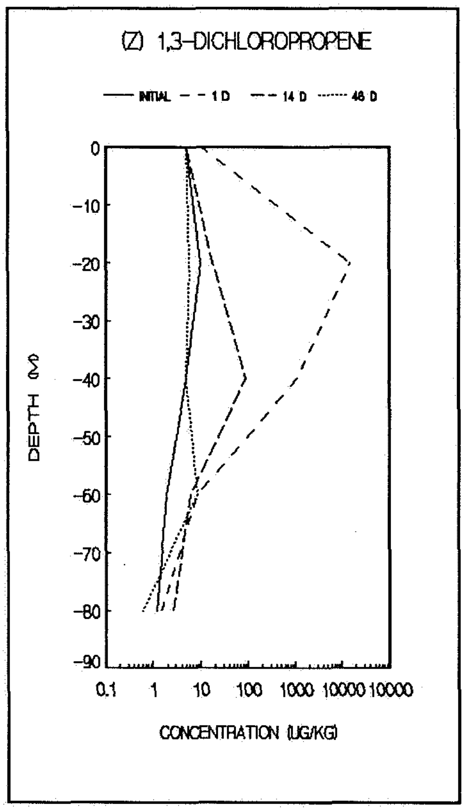
In order to calibrate the model parameters, some sorption and transformation experiments were done to estimate the transformation and sorption parameters of the pesticides. Some of these experiments are still in progress.

## 3 Results and discussion on (E) and (Z) 1,3-dichloropropene

About 150 $kg.ha^{-1}$ of 1,3-dichloropropene were injected at a depth of 0.6 m on 6 September 1989. The experiment on the movement, transformation and leaching of 1,3-dichloropropene started one week before and ended 105 days after application. The average soil temperature at a depth of 0.4 m amounted to approximately 17°C in September, in October to 12°C and in November to 8°C. The phreatic level ranged from a depth of 0.9 to 1.1 m. The samples of the four different depths, which were taken a week before application, contained low contents of 1,3-dichloropropene (Fig. 2).

The initial contents ranged from 11 $\mu g.kg^{-1}$ in the toplayer to 1 $\mu g.kg^{-1}$ at a depth of 0.8 m. The total initial amount of 1,3-dichloropropene up to a depth of 0.9 m depth was calculated on 0.15 $kg.ha^{-1}$. These small amounts may originate from the soil bound residue.

One day after applying dichloropropene roughly 95% of the fumigant was traced (Gas chromatography recovery 75%). Of this 95%, 99.7% was concentrated in the first and second layer. The contents of (E) and (Z) 1,3-dichloropropene in the toplayer were 11 $mg.kg^{-1}$ and 14 $mg.kg^{-1}$ respectively. At these initial contents the isomers are quickly transformed (Van der Pas, 1987. Smelt, 1989).



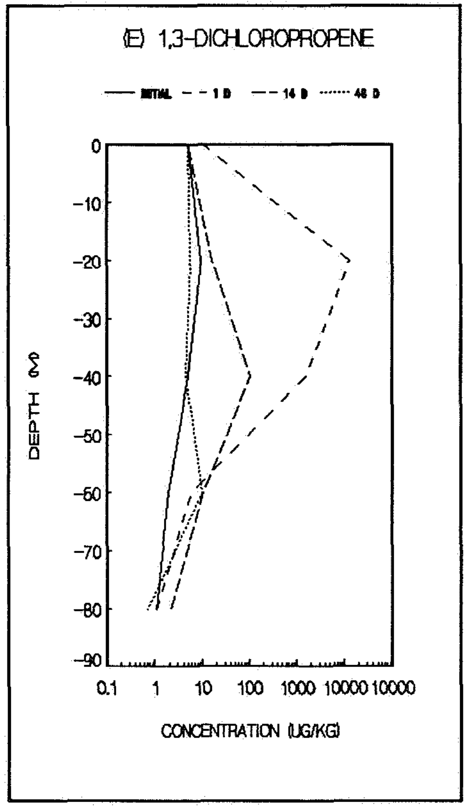




Figure 2. Concentration profiles in the experimental field one week before (initial) and 1, 14 and 48 days after application.

Two weeks after application only 1% of the initial amount was traced. About 7 weeks after application the concentration of 1,3-dichloropropene was almost identical to the initial concentration. Only at a depth of roughly 0.6 m the concentration was seven times higher than the initial concentration. The downward movement of 1,3 dichloropropene was caused by rainfall surplus.

In the month of September the accumulated drain discharge amounted to 9.3 mm, in October this was 16.8 mm and in November 9.8 mm. The relative low drain discharges were induced by low rainfall in this period (November 1989 was one of the driest months of November on record in The Netherlands). The first drain discharges were registered on 14 September.

Figure 3 shows that some leaching with rainfall occurred. However, this was less than 0.001% of the fumigated 1,3-dichloropropene.

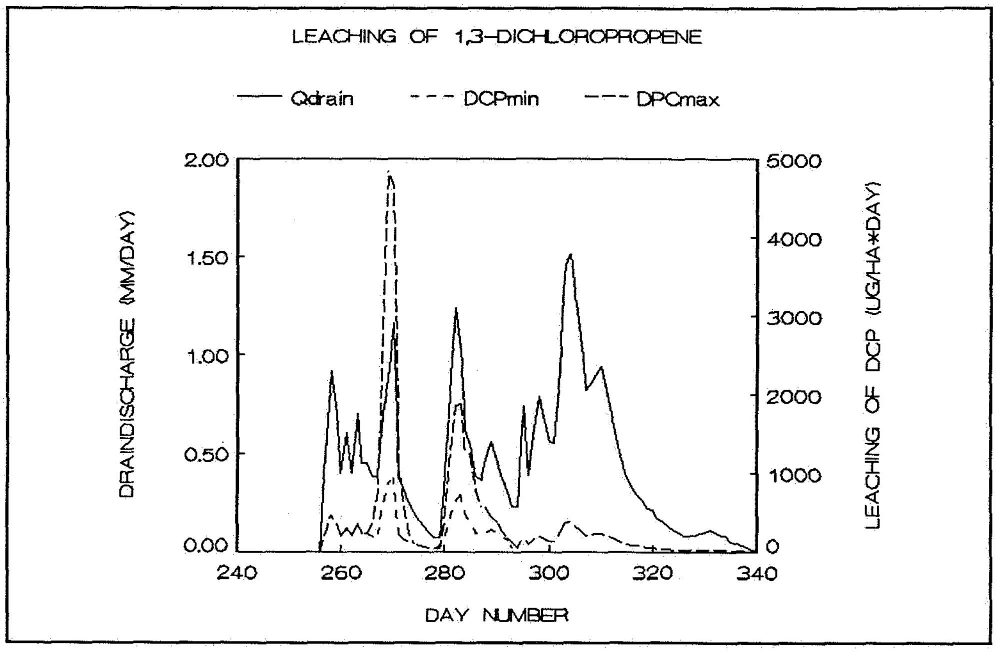



Figure 3. Drain discharges and the leaching of 1,3-dichloropropene. (DPCmin = minimum amount dichloropropene, DPCmax = maximum amount dichloropropene, Qdrain = drain discharge)

Since 1,3-dichloropropene was applied in a period with comparatively high soil temperatures and no rainfall occurring in the first 9 days after injection, the risk of leaching may be expected to be less than under circumstances with low soil temperatures and high rainfall, directly after injection. Furthermore, the extent of volatilization of the fumigant may be expected to be lower when soil temperatures and air temperatures decline.

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# TRANSFER OF NUTRIENTS IN A REGION OF INTENSIVE ANIMAL FARMING

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Abstract

The study of the quality of water in a rural environment involves the recording of rainfall and flow rates in order to quantify flows, evaluate the validity of the resources used to fight pollution and understand the transfer mechanisms.
This has been done on the Coët Dan drainage basin, an area which is characterised by very intensive farming with a large volume of battery farming.
The transport of nutrients in the stream has been studied by means of numerous analyses of water and matter, decomposition of the flow diagrams of spates, and a sampling strategy.
The in-depth study of the farms in the drainage basin has enabled a link to be established between this transport and the flow of nutrients through agricultural activity.
Nitrogen and phosphorus, which are used in excessive quantities in agriculture, enrich the natural waters by totally opposite mechanisms and the resources required to fight this pollution and protect the water must be adapted to these mechanisms.

## 1 Resources for research

In order to pinpoint the quantity and mechanisms of the discharge of nutrients, the CEMAGREF has studied their transfer in the Coët Dan

Basin in Naizin. This is a 1200 hectare basin in Central Brittany on impermeable shale soil.

The average annual precipitation established over an 18-year period is 720 mm with a standard deviation of 131 mm. The mean annual flow is 323 mm with a standard deviation of 171 mm. From 1976 onwards, the level of suspended matter, nitrogen and orthophosphates in the water was measured on samples removed manually from the outlet to the basin. We are continuing to remove and analyse samples of this type twice a month at the basin outflow.

Over the years, other parameters have been measured viz. ammonium, nitrite, total kjeldahl nitrogen, total dissolved phosphorus, organic suspended matter etc. Phosphorus is much more difficult to follow than nitrogen because of the highly irregular nature of the concentrations, the diversity of forms in which it is carried (orthophosphate, polyphosphate, organic colloidal phosphorus, specific phosphorus linked to calcium, aluminium, iron and organic matter) and the difficulty of sampling and analysing solid matter.

Because of this, the CEMAGREF has installed two samplers at the outlet to the basin. Regulated to a given water level threshold, they take samples at short, regular intervals when the stream is in spate. It is, indeed, during periods of spate that large variations in concentrations of phosphorus and suspended matter become apparent. The first sampler provides water samples that are used to measure concentrations in suspended matter, organic matter, orthophosphate and total dissolved phosphate. Nitrate and other forms of nitrogen are also measured using these samples. The second sampler removes 150-litre samples from which suspended matter is decanted for analysis.

During the research, we also removed samples of sediment from the bed of the stream in order to compare them with samples of soil and suspended matter. Tests were carried out on these samples in order to observe phenomena relating to precipitaion, sedimentation and release of phosphorus.

In order to establish the connection between these observations on water quality and the nutrients used in farming, a detailed study was undertaken of farming in the basin, including crop surveys, soil analyses, and an extensive enquiry among local farmers to pinpoint all the movements of nutrients in the form of fertilisers, animal feeds,

fodder, manure, crops, animals, and animal products.
An analysis of results produced an evaluation of fertilisation per field, per farming unit, and for the basin as a whole for nitrogen, phosphorus, and potassium.

## 2 Nitrogen transfer

Leakages of nitrogen from the basin usually take the form of nitrate nitrogen. The contentrations of nitrogen in water vary only slowly. Variations in nitrate concentrations as the ground water is refilled and emptied confirms that the chemical is supplied by infiltration water. This explains the decreased concentrations during periods of spate when the water running off the land, which is free of nitrogen, dilutes the water from springs.
The mean annual concentration has increased spectacularly, in proportion to the increase in animal farming within the basin.

| Year | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 |
| $NO_3$(mg/l) | 7 | 12 | 17 | 30 | 28 | 28 | 30 | 36 | 40 | 44 | 47 | 50 | 45 | 47 |

The relative stability observed over the past few years should not induce a false sense of security. 1987/88 was a particularly wet year with 987 mm of rain. The consequent run-off diluted the nitrate flow still further and lowered concentrations. The flow calculated for the year as a whole is nevertheless much higher than the flows in previous years. 1988/89, on the other hand, was exceptionally dry with a rainfall of only 546 mm (an 11-year cycle). Lower levels of nitrogen were leached from the land but the stock remained available as shown by the very high concentrations found during this winter.
Increased measures over the last few years have provided a reliable means of calculating the annual load of nitrogen by integration of instantaneous flows and the concentrations.
The loads amounted to : 65 tonnes in 1987-1988
20 tonnes in 1988-1989.

By comparison, the nitrogen levels used in agriculture in the basin give the following results:

| | | | |
|---|---|---|---|
| input | 395 tonnes | mineral fertilisers | 125 tonnes |
| | | commercial animal feeds | 228 tonnes |
| | | imported fertilisers | 38 tonnes |
| | | stock purchases | 4 tonnes |
| output from farming | 167 tonnes | manure exported | 9 tonnes |
| | | crops sold | 64 tonnes |
| | | milk, stock sales | 94 tonnes |

Excess nitrogen in basin: 228 tonnes
Total leakage of nitrogen in water: 20 to 65 tonnes

Undetected excess, i.e. between 160 and 210 tonnes, consists of volatilization of ammonia, volatilization of nitrogen gas after de-nitrification and, in certain years, soil enrichment.
It is therefore evident that only 42% of the nitrogen introduced into the basin's farming sector was actually used for agricultural purposes and that 10 to 30% of the remainder was drained off in the stream. This represents a considerable loss and may be one means of persuading farmers to decrease the quantities of fertiliser used and, in consequence, reduce risks to water.

## 3 Phosphorus transfer

### 3.1 Observations

A study of variations during 25 periods of spate showed that, during such periods, concentrations in suspended matter increase very rapidly, sometimes reaching more than 50 times the original concentration. They then decrease, while the flow rate continues to rise. The decrease in concentrations is much slower than the increase. Because of this, it is the first flow, when the water level rises most rapidly, which has the highest suspended matter content.

Concentrations in orthophosphates and total dissolved phosphorus follow the same type of evolution but concentration peaks more abruptly and maximum levels are attained before the maximum concentration in suspended matter. The increase in total dissolved phosphorus is larger than the increase in orthophosphate, which indicates that other forms of dissolved phosphorus migrate at the same time. This shows the need for very frequent measurements of concentrations and the need for continuous observation of flows. The staggered nature of the concentration peaks makes it useless to make any attempt to correlate.

These observations were repeated on each spate, with the following specificities:

- When several spates follow in rapid succession, the increase in concentrations of suspended matter, orthophosphate and total dissolved phosphorus become smaller;
- Concentrations increase with the magnitude of the spate;
- When the concentration time of the water is shorter, there is a decrease in the ratio of dissolved phosphorus to suspended matter.

Analyses of suspended matter show that they contain more phosphorus than sediment from the bed of the stream.

The phosphorus content of suspended matter varies little during periods of spate, representing larger instantaneous flows of phosphorus than of dissolved phosphorus. Except periods of spate, the water contains almost no suspended matter and, therefore, very few phosphorus-bearing particles.

The following flows were measured over the last two years:

| YEAR | 1987-1988 | 1988-1989 |
|---|---|---|
| Water | 5 987 000 cu.m | 1 490 000 cu.m |
| Suspended matter | 520 tonnes | 72 tonnes |
| Orthophosphate | 1 045 kg P | 251 kg P |
| Other dissolved phosphorus | 2 050 kg P | 226 kg P |
| Phosphorus particles | 1 060 kg P | 150 kg P |
| Total phosphorus | 4 155 kg P | 627 kg P |

The role of spates and flowing water in general is of vital importance in determining the transfer of phosphorus. So, more than 70% of the possible values of the yearly phosphorus flows may be between those of 1987-1988 which was a very wet year and 1988-1989 which was an exceptionally dry one.
It is impossible to predict any evolution over the next few years as in the case of nitrogen because of irregularities caused by deviations in rainfall, which completely mask the enrichment of the environment concerned.

## 3.2 Drainage mechanism

Laboratory experiments have shown that sediments very quickly release almost all their phosphorus content when they become suspended and that the phosphorus content fixes again gradually before resedimentation. An analogy with variations observed in the stream explain the phosphorus drainage mechanism. Dissolved phosphorus mineralises partially and more slowly, until it is changed into orthophosphate.
During storm periods water from water logged areas and less permeable areas washes away animal waste dust and matter from tractor wheels. In fields, erosion detaches particles from the soil. Such particles have been enriched with phosphorus from fertilisers and manure that have been spread over the land. In the river bed, the water is accelerated and in turbulence, causing the sediment to ascend from the bottom and form a suspension. All this matter then releases phosphorus, which explains the high concentrations found at the start of periods of spate.
When the flow rate of the water has stabilised and the laminar flow is almost reached, the phosphorus begins to attach itself to the suspended matter again prior to sedimentation. This explains why the dissolved phosphorus peak precedes the suspended matter peak and why it is of a shorter duration. It also explains why sediments have a lower phosphorus content than suspended matter. Matter that deposits in the shortest time has less time to fix the phosphorus, while matter that takes longer to deposit is carried further by the water and fixes phosphorus as carried down by the stream in spate.

### 3.3 Phosphorus flow

The evaluation of the phosphorus used in farming in the drainage basin as calculated on the basis of the enquiry gives the following results:

| | | | |
|---|---|---|---|
| input | 92.6 tonnes | mineral fertilisers | 26.4 tonnes |
| | | commercial animal feeds | 48.7 tonnes |
| | | imported fertilisers | 15.8 tonnes |
| | | stock purchases | 1.7 tonnes |
| output from farming | 35.5 tonnes | manure exported | 2.6 tonnes |
| | | crops sold | 10.8 tonnes |
| | | milk, stock sales | 22.1 tonnes |

phosphorus surplus on the basin: 57.1 tonnes
leakage of phosphorus by the stream: 0.6 to 4.2 tonnes

The surplus, i.e. between 52 and 57 tonnes every year, is stored in the form of soil enrichment, as confirmed by the results of the soil analyses. This corresponds to an enrichment of 46 kg of phosphorus per hectare per year. The enrichment benefits only the top layers of soil, which are susceptible to erosion, and therefore increases the risk of leakage of phosphorus into the stream every year.
The quantity of phosphorus lost in this way is negligeable compared to the total quantity used in agriculture. Nevertheless, it constitutes the limiting factor for eutrophication and is therefore of enormous importance with regard to water quality. This being so, a reasonable level of fertilisation will be an inefficient way of controlling phosphorus release as it is rather more dependent on climatic conditions and stock than on the year's enrichment.
Only 38% of the phosphorus supplied was actually taken up by agriculture. The stock-breeding units in the basin produce such high quantities of phosphorus that, even if there were no exogenous additions of fertiliser, the soil would still be enriched and the leakage of phosphorus into the stream would still increase. The present

soil amount of phosphorus in the soil is such that, even if supply and outflow are in balance, leakage would still occur for the next few decades.

The mechanism observed, however, opens the way for a reduction in leakage of phosphorus by trapping the first runoff. To achieve this, there must be areas to store the first runoff, having the highest phosphorus content, and subsequently allowing the phosphorus to precipitate onto the suspended matter. The phosphorus-rich matter can then be collected.

# FITTING A CONCEPTUAL HYDROLOGIC MODEL ACCOUNTING FOR NITRATE LOSS IN AN AGRICULTURAL REPRESENTATIVE BASIN

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Abstract

Nitrate has been measured since 1975 at the outlet of a subcatchment of the Orgeval representative basin in an area of intensive croping, mainly of cereals.
Each year, a map of land use, together with inquiries on fertilisers, allows to estimate the input and the quantity of nitrogen exported in crops. A model of daily concentration of nitrate has been designed, which encompasses chemical reactions within the soil, and nitrate leaching, governed by variables of the hydrologic model GR3. A model of denitrification in the river has been also added.
The model gives good results, even for exceptional meteorological situation. Simulation of modified agricultural practice is presented. Difficulties of using the model in other basins less instrumented are discussed.

## 1 Introduction

The Melarchez basin (7 km$^2$) was chosen as the application site. It is the most upstream subcatchment of the Orgeval representative basin (104 km$^2$) which is located in the east part of the Paris basin in France. 90% of its surface is cultivated of which 80% is subdrainaged. Wheat, barley and corn are the major crops. Beneath the upper soil there is an impermeable layer that makes the deep percolation negligible. Each year, a map of land use and investigation of fertilization to each crop are made in July.

The first research gave estimation of the different terms of yearly nitrogen budget and established concentration/discharge relationship (Belamie, 1982), the further step was the modeling of daily concentration.

## 2 Hydrologic model

A schematic presentation of the hydrologic model very similar to GR3 model (Michel et al, 1989) is shown in the Fig. 1. The model is run at daily time step with precipitation and mean air temperature as input. The potential evapotranspiration, estimated from temperature only, is reduced to actual evapotranspiration in function of the soil reservoir's level S (Fig. 1). Besides the evapotranspiration, the level

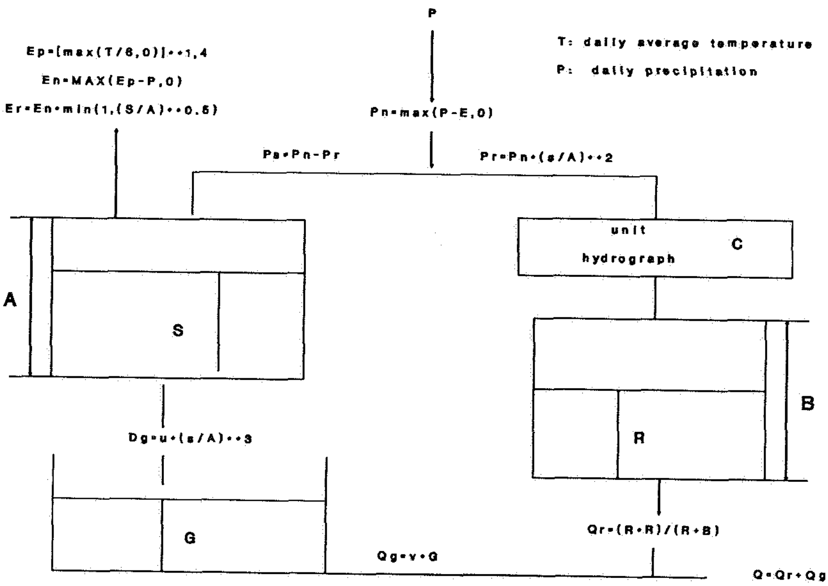


Figure 1. Hydrologic model

of the soil reservoir governs also the production of net rain Pr to the reservoir R and the percolatio Dg to underground water. A syntheticunit hydrograph is incorporated to reproduce the basin's response time. The total outlet flow consists of the rapid flow from reservoir R and the underground flow from the reservoir G. Five parameters in total need to be calibrated, but only 3 when the transfer to reservoir G can be omitted, which is the case for Mélarchez.

## 3 Nitrogen model

The nitrogen model (Fig. 2) includes the major processes determining inputs, internal transformations and outputs of nitrogen in arable soils as well as denitrification in river water. Soil inputs include inorganic fertilizer and atmospheric deposition.

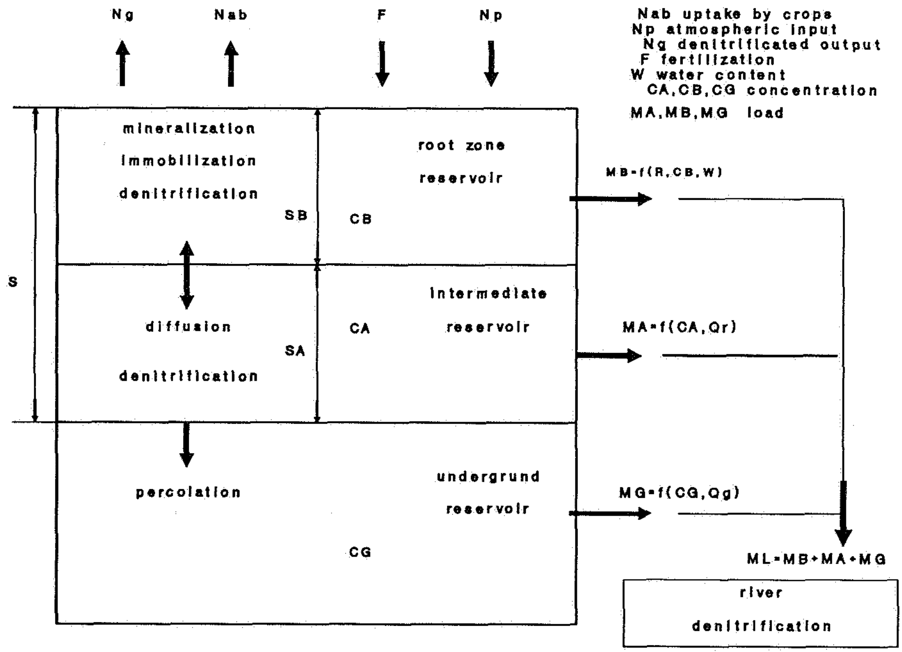


Figure 2 Nitrogen model

### 3.1 Dissolution of inorganic fertilizer by rain.

The chemical fertilizer is applied to soil in solid form. We employ a parameter to control the dissolution of fertilizer by rain. Another function of this parameter is to correct the fertilizer spreading date because all the farmers don't spread their fertilizer on the same day.

DILU = Fd*P

where

DILU: dissolved fertilizer by rain P

Fd: parameter

### 3.2 Biochemical transformations within the soil.

The forms considered of soil nitrogen are nitrate and organic nitrogen. The processes considered are mineralization, immobilization and denitrification. All inputs in form of ammonium are assumed to be oxidized rapidly to nitrate. These transformations are all calculated as a first-order process. The rates of the reactions are regulated by the soil temperature (optimum at 35°) and water content (optimum at field capacity for mineralization and immobilization, optimum at saturation and effective only near to saturation for denitrification). The soil temperature is simulated as equal to the average air temperature of the 20 days prior to the date considered and the soil moisture is linear with the soil reservoir's level S (see Fig. 2).

### 3.3 Uptake by crops.

We utilize Michealis-Menton approach to simulate plant uptake.

Fn(t) = B*f(t/T)*[NO3]/([NO3]+kab)

where

B: total potential uptake

Kab: Michealis-Menton absorption coefficient

f(t/T): reduced unit function $\int_{0}^{T} f(t/T)dt = 1$

T: plant growing period

Furthermore, the crop's uptake of nitrate will be reduced if soil moisture is below field capacity.

### 3.4 Leaching.

In the leaching simulation, we redivided vertically the soil reservoir of the hydrologic model into two reservoirs, one named root zone reservoir (B) and another intermediate reservoir (A). All inputs come to root zone reservoir where take place the biochemical transformations and plant absorption. Leaching, assumed to be proportional to the level of reservoir R when R is high and negligible when R is low, is given by the following formula:

$$MB = PL*(R/R0)*e^{\min(0,(R-R0)/R)}*CB*(W/Ws)$$

where

PL: leaching parameter

CB: nitrate concentration of root zone reservoir

R0: threshold

W,Ws: soil water content and water content at saturation

In the intermediate reservoir, only denitrification takes place. The horizontal leaching MA and the deep percolation (Fig. 3) are both proportional to the reservoir's concentration and their corresponding water flow. The mass exchange between these two reservoirs is simulated with a diffusion approach in which the governing variable is the concentration gradient. Another parameter of diffusion (DF) is therefore added. Finally, the concentration of the underground reservoir is assumed to be constant.

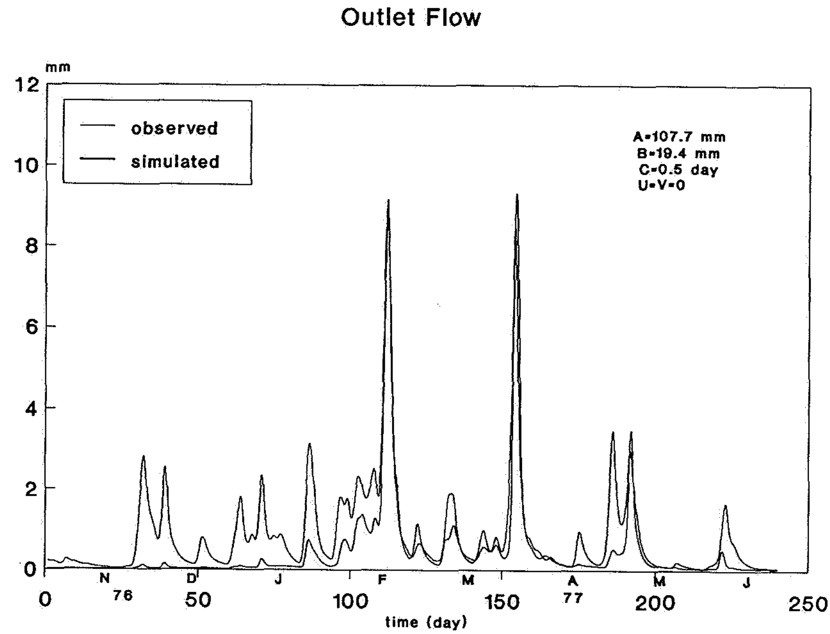


Figure 3. Outlet Flow

### 3.5 Denitrification in the river.

The nitrogen dynamics in a river is based on a mass balance approach for a non-conservative variable and can be written for a reach cell as (Whitehead et al, 1984):

$$dC/dt=Qi*Ci/Ve-Q*C/Ve-K*10^{0.0293Tw}/d$$

here Ci and C are input and output concentration respectively; Qi and Q are input and output flow; Ve is the effective volume of the cell; d is river depth; K is denitrification rate and Tw is water temperature and can be simulated with a statistic model (P. Morceau et al., 1986) which utilizes air temperature as input. In a small catchment this submodel gives minor contribution to total load and is necessary only for low flow periods. On the contrary, it is a major part, and should be improved, for large basins.

# 4 Model application

The model was calibrated against the daily observed outlet flow and nitrate concentration over a period of three years and tested over the following two years. The values of the parameters are separately presented in Fig. 3 and Fig. 4. Fig. 3 shows an over-estimation in November and December of 1976 and January and February of 1977 for flow simulation. This is caused by the 1976's extreme draught in Europe. In Fig. 4 the nitrate concentration is generally well reproduced. The correlation coefficients for flow and concentration simulations over 5 years are of 0.84 and 0.69 respectively.

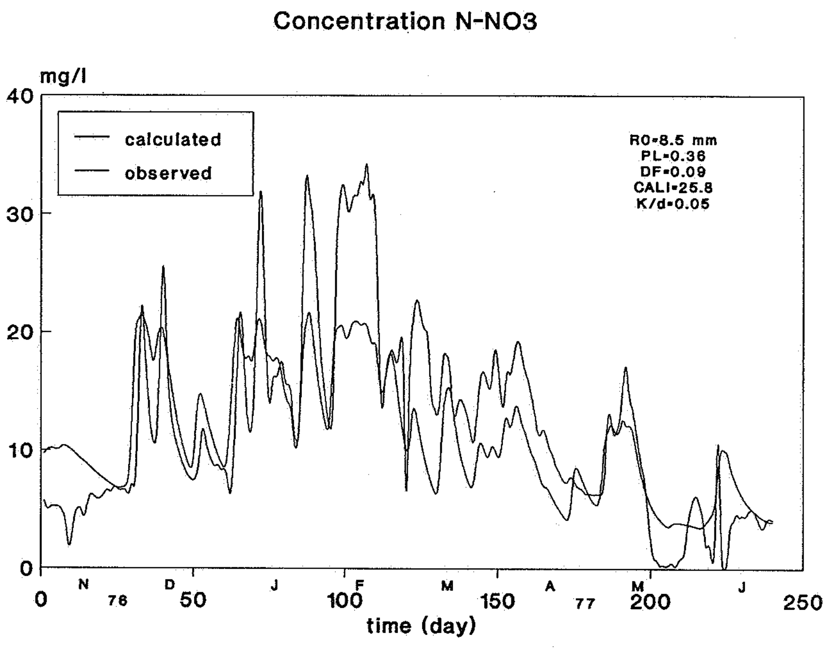


Figure 4. Concentration N-NO3

The simulation of adding an autumn mustard following barley and wheat shows some interesting reduction of nitrate leaching in winter and spring, but the model is most sensitive to the hydrologic variables, that's to say the level of reservoir R and the soil moisture. The experimental verification is not possible on a basin of this size, but change in farm practice is now being performed on a plot which is the upstream catchment of a spring.

We have tried to apply this model to the Né basin (529 $km^2$) in south west France. The result of flow simulation is much better than the Melarchez's but the nitrate concentration is worse. The raisons can be, first of all, the big difference of dimension between the two basins, and secondly the lower frequency of concentration measurements (eight per year).

## 5 Discussion and conclusion

The modeling of nitrogen in the hydrological cycle would in principle require the knowledge of water flow and storage. In fact, it was shown that the equation governing nitrogen could be assumed to be controlled by variables of the empirical-conceptual hydrologic model which have no clear physical meaning. If the model does not fully account for all processes and can not be easily transfered to another basin, it allows, however, to simulate moderate change in meteorological conditions, quantity of fertilizers, or modification of uptake by vegetation and can be used for assessing non point pollution management.

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# POSTERS

# HEAVY METAL CONTAMINATION OF GROUNDWATER IN INDUSTRIAL ESTATE OF ALIGARH CITY, INDIA

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## Abstract

To study the concentration of heavy metals in groundwater of industrial estate of Aligarh City, India, samples were collected from different sources. Further, these samples were analysed and results were compared with standard guidelines prescribed by WHO, 1985. Study reveals that the concentration of heavy metals like Fc, Cu, Mn, Cd and Pb are much higher than the permissible limits in the case of shallow groundwater while well within the limits in case of deep groundwater. Possible sources of these metal contamination in shallow groundwater was traced out from metal processing industries discharging enormous amount of effluents with higher concentration of heavy metals. Treatment of these effluents before letting them into drainage system, and their disposal on land should be taken as a preventive measure to protect the present environmental degradation.

## 1 Introduction

Haphazard urban development without adequate attention to sewage and waste disposal is one of the most widespread causes of pollution. Rapid industrialisation without any provision of proper treatment and disposal of waste and effluents is another source of pollution

(Karanth, 1987). Aligarh City, the area under review is no exception as it is one of the fast developing industrial city in state of Uttar Pradesh, India. The establishment of industries are disturbing the environmental balance and thereby contaminating the groundwater with heavy metals.

## 2 Geology and Hydrogeology of the area

Aligarh city forms one of the important city centres of the Ganga-Yamuna Doab. The district is divisible into three distinct physiographic units: the western and eastern uplands and the central depression. The area under review (Fig. 1) falls under the sub-tropical climatic zone. The monsoon breaks in the second week of June with 90% of the rainfall in July and August. The average annual rainfall is 759.1 mm.

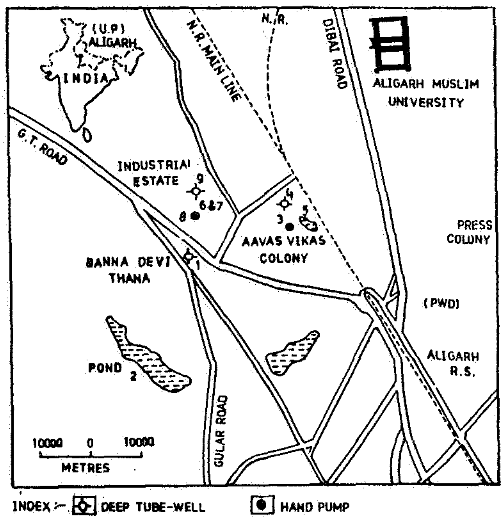


Figure 1. Showing sampling locations in industrial estate of Aligarh city, India

The sub-surface geology consists of Bhandar Group of Upper Vindhyan red shale. On the eroded and upturned surface of these rocks, Quaternary sediments were deposited. The depth to bed rock is

340 metres below ground level (m.b.g.l.). There occurs a three-tier aquifer system which lies in the depth range of 9-66, 99-110 and 179-201 m.b.g.l. The aquifer material consists of fine to medium, grey micaceous sand. The depth to water level ranges between 12.00 to 14.00 m.b.g.l. The regional groundwater flow is from northwest to southeast. In the study area the groundwater serves the only source of water supply for domestic, agricultural and industrial requirements. During the past one decade the excessive withdrawal of groundwater, much higher than quantum of average annual recharge, has induced a declining trend of water level in the area. (Ahmad et al., 1988).

## 3 Results and Discussion

The concentration of heavy metals in groundwater, surface water, city wastewater and industrial effluents have been given in the table I.

Table 1. Average concentration of heavy metals in ppm
(Using GBC-902, Double Beam A.A.S.)

| Source | Fe | Cu | Mn | Pb | Cd | Cr |
|---|---|---|---|---|---|---|
| Hand Pump | 1.950 | 0.253 | 0.250 | 0.061 | 0.004 | 0.001 |
| Deep Tubewell | 0.085 | 0.013 | 0.132 | 0.020 | 0.003 | BDL |
| Pond | 0.290 | 0.790 | 0.054 | 10.420 | 0.004 | 0.003 |
| City effluents | 1.564 | 0.371 | 0.094 | 0.175 | 0.016 | 0.113 |
| Industrial " | 6.599 | 0.402 | 2.515 | 7.660 | 0.045 | 0.173 |

BDL - Below detection limit

Table shows that the heavy metal concentrations are on the higher side than the permissible limits. The high concentration of Pb in the pond water on Gular Road is found as 10.420 ppm followed by industrial complex effluents as 7.66 ppm and 0.1759 ppm in city effluents respectively. The concentration of Pb in the shallow aquifers was observed 0.0610 ppm. All these levels are dangerous as Pb is a serious body poison. Cadmium in the water samples is found within the limit while it is present in the effluents in high concentrations i.e. 0.0458 and 0.0169 ppm. Chromium is not present in detectable amounts in deep groundwater samples but its concentration in effluents is very high. Manganese levels are high in water samples. In all the samples analysed, the level of Cu is higher than the permissible limits. However, it was observed that the concentrations of all these heavy metals decrease with the depth.

## 4 Conclusion

Study reveals that the shallow groundwater is contaminated with heavy metals. Since the quality of water from shallow aquifer is not suitable for drinking purposes, deep aquifers need to be exploited to avoid health hazards. Proper arrangement for the treatment of municipal and industrial wastewater should be undertaken because it is likely to spread over the entire lateral extent and vertical thickness of the aquifer zones. Recharge through surface water source be managed to arrest the declining water level and dilution of contaminated shallow groundwater to ensure the better environment for the area and its inhabitants.

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# STREAM CORRIDOR MANAGEMENT: WATER QUALITY IMPLICATIONS

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## 1 Background

The existence of intensive agricultural practices within catchments may exert a minimal impact on stream water quality if a stream corridor management strategy is adopted. In the light of a possible forthcoming E.C. directive (COM 1988(708)Final) on surface water pollution control the establishment and assumed effectiveness of buffer zones seems a political reality. This paper presents evidence of "buffering processes" operating in a floodplain with particular attention to nitrogen-based solutes derived from upslope sources.

## 2 Site Description

A study of the buffering effectiveness of two types of floodplain vegetation is being carried out on the floodplain of the River Leach a tributary of the Upper Thames. Slopes above the floodplain are underlain by Great Oolite limestone; soils are of freely-drained Sherborne Series with intensive arable farming. The floodplain lies on impermeable Fullers' Earth clay. In each plot (grassland site and a poplar plantation site [Populus Italica]), a grid of bore-holes within the floodplain and adjoining slope allows the dimensions of saturated zone to be monitored and water samples to be collected. The grassland site has a grid of 24 holes (6 holes upslope by 4 holes up-valley), while the poplar site consists of 7 holes upslope and 2 holes up-valley; this article will confine itself to the grassland site. Several springs and the main river are also monitored for discharge and water quality.

Nitrogen analysis of the water samples is divided into nitrate ($NO_3$-N), nitrate ($NO_2$-N), total oxidised nitrogen ($NO_3$-N + $NO_2$-N = TON-N) and ammonium ($NH_4$-N) species.

## 3 Preliminary Results

Preliminary results suggest a clear distinction between water derived from upslope zones and floodplain water. Figure 1 shows that water enters the floodplain with high TON-N concentrations (2.18 mg-N$l^{-1}$ [±0.03]) but that within a few metres, its concentration has fallen markedly (0.91 mg-N$l^{-1}$ [±0.03]).

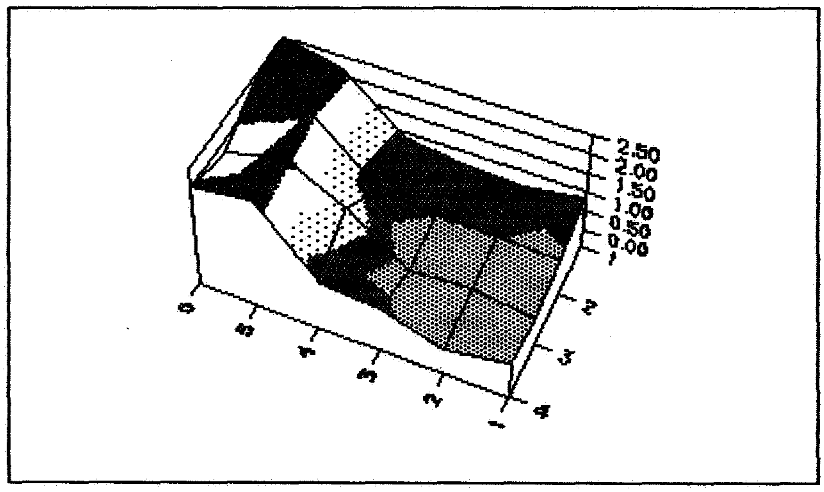


Figure 1. Mean TON ($NO_3$-N + $NO_2$-N) concentration (mg-N$l^{-1}$) in December 1989 at the grassland site

It can be concluded that this is evidence of loss of upslope TON by various mechanisms (e.g. assimilation, denitrification, dilution) provided that it can be shown that the bore-holes are hydrologically connected and that there is flow across the floodplain. Observations of the watertable elevation on the floodplain demonstrate that a

significant hillslope hydraulic gradient impinges on the floodplain, but that flow is not directly to the stream banks.
Groundwater derived from upslope sources flows across the floodplain to a buried channel in the centre of the floodplain, from where water flows in a down-valley direction (Figure 2).

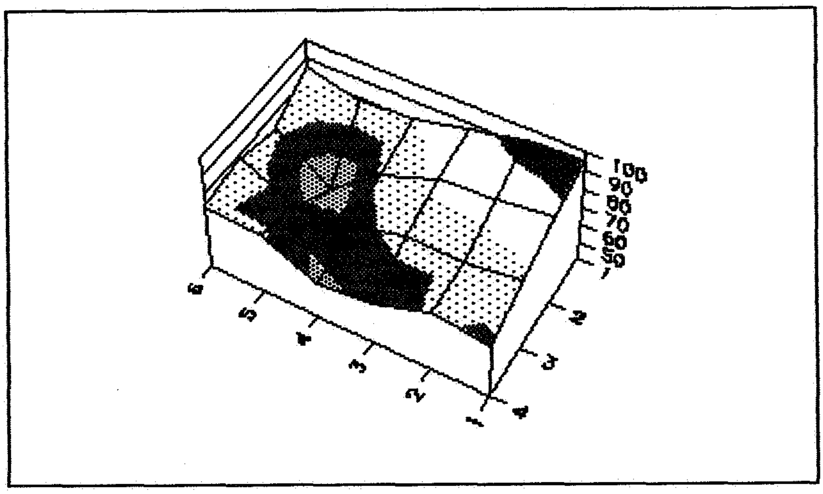


Figure 2. Mean watertable (cm above an arbitrary datum) elevation in December 1989 at the grassland site

Taking these effects together the grassland site under study does show a loss of upslope-derived TON with minimal down valley export of TON. On the basis of observations made to date, the 'buffering' process has occurred throughout the year, unlike the uptake of TON by in-stream vegetation which appears to be strongly seasonal process, as is illustrated by figure 3.
Excessive in-stream vegetation growth in the River Leach chokes the channel in summer. In autumn, the degeneration of this vegetation could be related to higher than expected surges of ammonium-N, associated with quick-flow events, which might prove toxic to fish.

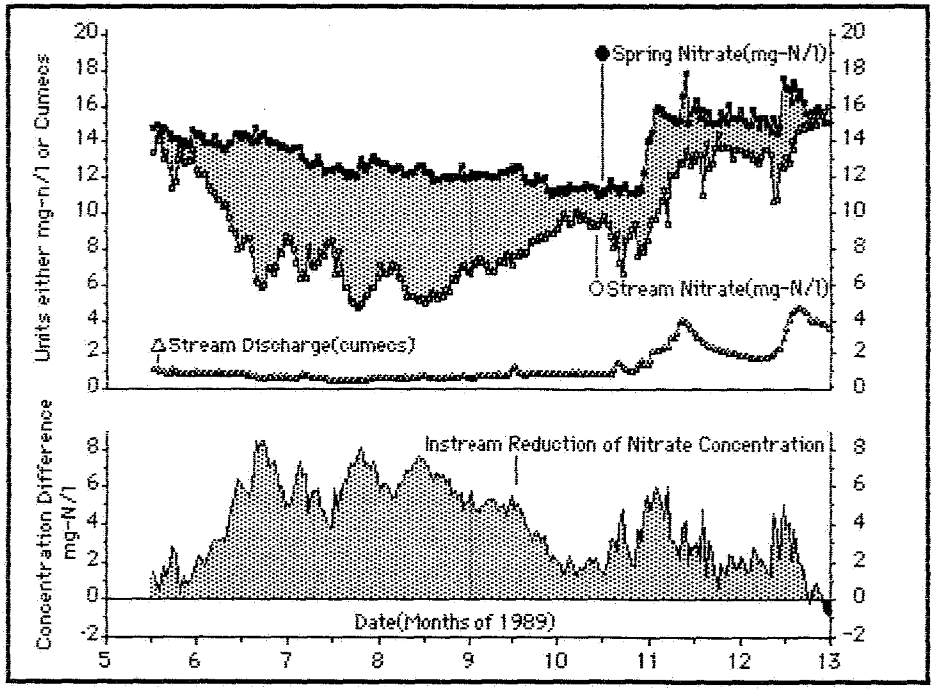


Figure 3. Daily mean values of the Discharge on the River Leach (cumecs), and stream and spring TON concentrations (mg-Nl$^{-1}$)

## 4 Conclusion

Given the consistently high TON-N concentrations of the catchment springs (Figure 3) and upslope-derived water (Figure 1), the impact of the loss of TON-N within the floodplain can be seen to be critical in the control of stream TON levels. The maintenance of only a stream bank-side ecotone has a very limited role in controlling in-stream water quality. The accepted scientific definition of 'riparian' must be broadened to include a significant portion of the floodplain.

Effective stream corridor management is needed to mitigate the impact of non-point pollution from intensive agricultural land.

## Acknowledgements

Nick Haycock is a CASE research student funded by the Natural Environment Research Council (GT4/88/AAPS/63) and the Water Research Centre (WRc), Medmenham. Additional support was provided by Keble College, Oxford, and the John Martin's Charity, Evesham.

# AN ATTEMPT TO VERIFY A MODEL WITHOUT CALIBRATION
## A STEP TOWARDS REGIONALIZATION

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Abstract

A major objective of mathematical modelers is the prediction of reality without calibrating model parameters. In hydrology this means to forecast streamflow and other elements of the water balance from meteorological input by deriving catchment parameters from existing or easily accessible information (e.g. maps and direct measurement) rather than calibrating them. A distributed, deterministic and physically based continuous hydrological model has been applied to numerous gaged catchments in the Federal Republic of Germany during the last decade. The resulting sets of parameters showed some systematic behaviour and narrow plausibility boundaries due to the physical significance of the parameters used. Standardized parameter estimation procedures could be developed for determining land-use, geometric and soil parameters. To determine the inaccuracy or uncertainty based on this parameter estimation, the model was applied to seven small representative catchments in Northrhine-Westphalia without calibrating the model. The comparison with measured outflow can be interpreted as verification without calibration. The results are quite encouraging for most catchments; the goodness of fit indicates that derivation of parameters without further adjustment is possible, if some more effort is invested into initial estimation.

## 1 Introduction

The estimation efforts for parameters in hydrological models can be reduced to a considerable extent, if the parameters have a clear physical definition. A major problem is that the estimated parameters, despite their physical meaning, are indices of the physical values rather than true values. Spatial and temporal averaging are the main reasons. A continuous deterministic, distributed and physically based model has been frequently applied to numerous catchments in Northrhine-Westphalia, FRG. As a result an estimation procedure could be developed for the soil moisture component of the model, based on soil maps, Scale 1:50000. The procedure was applied for the estimation of soil parameters of 7 representative catchments, for which the measured streamflow was available. The poster reports about the model applied, the catchments modeled and the results obtained.

## 2 The Model

The structure of the model applied is given in Figure 1. For rural watersheds the key module of the model is the soil moisture component. This is explained in Figure 2. Soil parameters used in the algorithm are rooting depth, porosity, permanent wilting point, field capacity, hydraulic conductivity of the dry soil surface and saturated hydraulic conductivity at rooting depth.

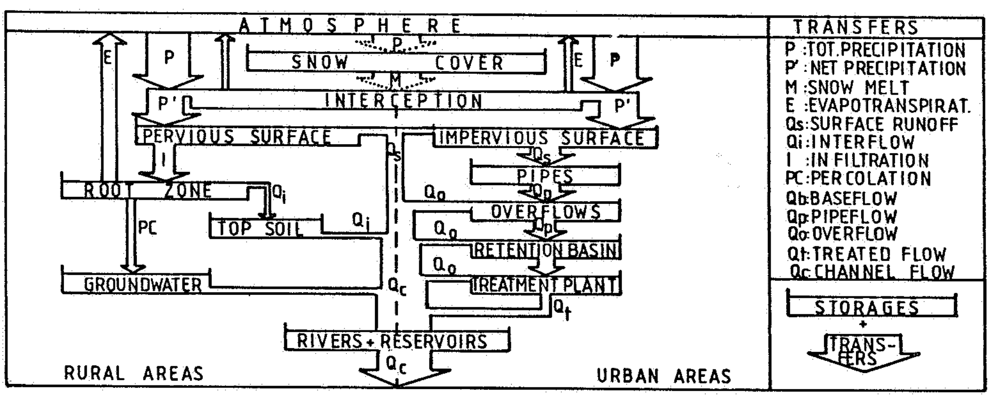


Figure 1. Structure of hydrologic simulation model

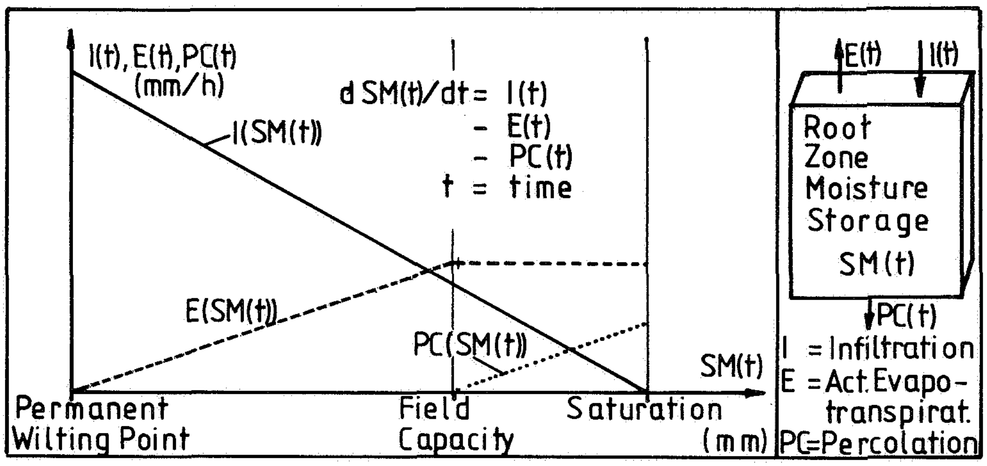


Figure 2. Mathematical assumptions for the soil moisture module

The estimation of the parameters is based on an official soil map, containing the type of soil and some of the parameter values needed. Other parameters are included in pedological handbooks. According to long experience the parameters for soil conductivity are finally multiplied with constant correction factors.

## 3 The catchments

Table 1 gives an overview of the main catchment characteristics.

Table 1. Main characteristics of catchments investigated.

| Catchment Name | Area km2 | Mean Elev. | Land-use | Soil |
|---|---|---|---|---|
| Nauholzbach | 3.95 | 521 | 98% forest | sandy loam |
| Helgersdorf | 0.35 | 460 | 94% forest | sandy loam |
| Preisdorf | 8.52 | 550 | 95% forest,5% grass | sandy loam |
| Grieselsiefen | 0.30 | 640 | 91% forest | clay |
| Solchbach | 2.17 | 358 | 98% forest | loam |
| Wehebach | 2.38 | 466 | 35% forest,64% grass | sandy loam/clay |
| Esterbach | 0.49 | 610 | 99% forest | stony loam |

## 4 Results

The goodness of fit is described by some specific hydrologic deviation measures. Although the correlation coefficient (measured versus computed flow) alone is not suitable to describe the quality of simulation runs, it is used here as a first indicator. Table 2 contains the correlation coefficient for the years simulated (daily values) for each catchment.

Table 2. Correlation coefficients for the catchments simulated

| Catchment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nauholzbach | .89 | .49 | .78 | .33 | .87 | .73 | .89 | .83 | .76 | | |
| Helgersdorf | .74 | .92 | .93 | .67 | .83 | .30 | .86 | .82 | .89 | .86 | .82 |
| Preisdorf | .93 | .76 | .66 | .78 | .79 | .85 | .89 | .82 | | | |
| Grieselsiefen | .77 | .91 | .82 | .07 | .85 | .88 | .14 | .77 | | | |
| Solchbach | .73 | .69 | .72 | .79 | .85 | .83 | .86 | .85 | | | |
| Wehebach | .69 | .81 | .76 | .80 | .73 | .76 | .81 | .73 | | | |
| Esterbach | .73 | .70 | .83 | .86 | .61 | .67 | .83 | | | | |

Some years with very poor correlation can be found, which is due to inverse weather conditions during snowmelt periods. In general, however, the results are encouraging. Except for the Solchbach, simulated yearly runoff volumes deviated only between 1 and 23 % from the measured volumes. Relatively high deviations occured during low flow periods, which is caused by a known systematic modeling weakness.

## 5 Interpretation

The investigation proved that streamflow and other components of the hydrological cycle can be predicted with adequate accuracy for ungaged watersheds. To be successful, longterm experience and a sound data base for the description of the physical characteristics of the watershed are essential. Ongoing statistical analysis of calibrated parameter sets will further reduce the uncertainty in model prediction.

# INDEX OF AUTHORS

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