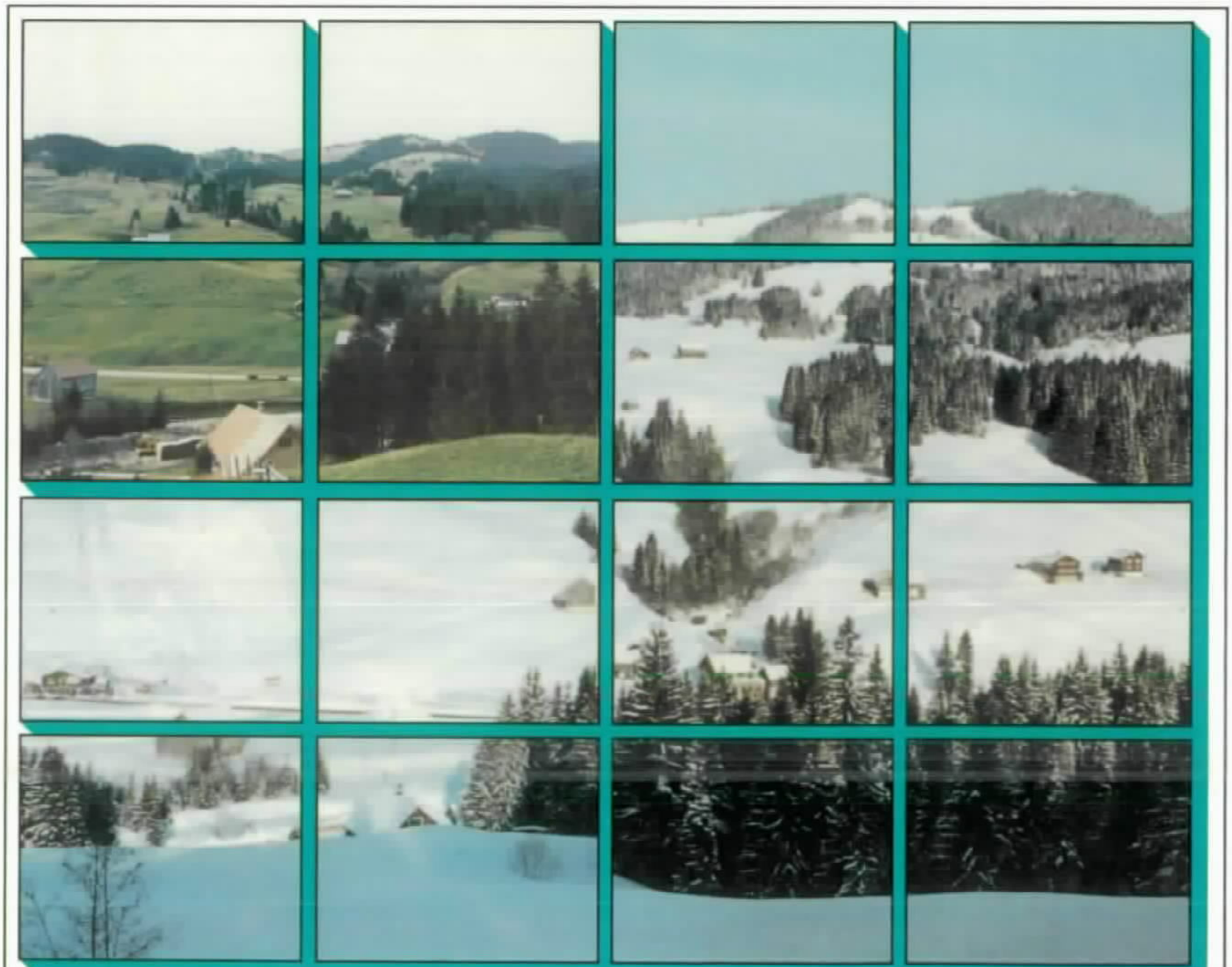
Institute of Hydrology

Report No. 120

Methods of hydrological basin comparison



Natural Environment Research Council

Report No. 120

Methods of Hydrological Basin Comparison

Edited by M. Robinson

Proceedings of the Fourth Conference of the European Network of Experimental and Representative Basins

University of Oxford
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Foreword

It is the aim of the European network of Experimental and Representative Basins (ERB) to provide a basis for international cooperation. The ERB was in its 6th year of existence when the conference on Methods of Hydrological Basin Comparison took place in Oxford, UK, from September 29 to October 2, 1992. The network Inventory (ICARE - Inventory of Catchment Research in Europe) now contains 92 basins in 10 countries. The methodologies used in basin comparison studies are of special importance and should be used with care. For this reason the conference focused on methods rather than on results of basin comparison studies.

ERB appreciates the support from the International Association of Hydrological Sciences. We are especially grateful to the UK Institute of Hydrology for organising the conference, and are pleased to see the publication of the papers as a report in the Institute's series. We hope that this publication finds a wide distribution among operators, practitioners, and researchers who work in hydrologic basins. We would like to strengthen the methodologies of basin comparison even more in the future. As the Inventory and the data become used more frequently and internationally we hope that this collection of papers will be widely used. We are grateful for the efforts of the editor of the report, Dr Mark Robinson, and for the wide support from the Institute of Hydrology.

Dr Hans M. Keller
ERB Coordinator

The European Network of Experimental and Representative Basins was established to encourage the collaboration and exchange of experiences and techniques between scientists. Its success is evident from its continued growth over the last six years, to now include most countries in western Europe, and an increasing number from central Europe.

This type of international contact is of growing importance with the closer political links between European countries, together with the accelerating pace of land use change and of 'transboundary' issues such as 'acid rain' as well as global issues such as climate change, which cannot be tackled at a merely national level. Basins are integrators of the complex processes within them, and their long term records are becoming increasingly valuable as we look towards the challenges of the next century. This timely conference brought together experts from across Europe to discuss and to pool their experiences. The conference was attended by approximately fifty specialists from 14 countries in Europe and North America. There are obvious benefits from such exchanges, and there are close links between the ERB Network and shorter-term more intensive studies such as the ENCORE and FRIEND projects.

Prof W.B. Wilkinson
Director of UK Institute of Hydrology

Preface

This volume comprises papers presented at the fourth conference of the European Network of Experimental and Representative Basins (ERB), which was founded in 1986.

The main aims in establishing the Network were to encourage international contacts between scientists and research teams through meetings and data exchanges, and to encourage the creation of joint research projects.

The network is managed in Europe by National Correspondents nominated by the Unesco - IHP National Committees of the member countries - Belgium, France, Germany, Italy, Netherlands, Portugal, Spain, Switzerland, UK and, our newest members, the Czech and Slovak Republics.

The ERB organises International Conferences at two-year intervals. To date these have been

October	1986	Aix en Provence, France
October	1988	Perugia, Italy
September	1990	Wageningen, Netherlands
September	1992	Oxford, England

In addition, an ERB Newsletter is published approximately twice yearly and distributed to 250 scientists worldwide. This covers information about national and international activities, and projects, research findings and publications, as well as progress with the ERB Inventory.

The ERB Inventory (ICARE) provides a computer database of nearly 100 basins, including their physical characteristics, instrumentation, data, research aims and key publications. The database is maintained and continuously updated by the CEMAGREF in Lyon, France, with information provided by the National Correspondents.

The ERB Inventory can be accessed to obtain information about basins which fulfil certain criteria; for example it has been used in the FRIEND Project to identify small research basins in northern and western Europe concerned with physical processes of streamflow generation.

The first phase of the ERB Network (1986-91) was concerned with establishing the Network, identifying basins and obtaining descriptive data. Scientific topics of common interest were discussed and several research teams prepared joint research bids to the CEC.

The second, and current, phase of the ERB Network has been concerned with moving on from the establishment of the Network to its use. The ERB Inventory has reached a level of completeness where it can be used operationally by scientists to exchange and analyse research results. This offers wide opportunities to perform comparative basin studies.

Basin comparisons have been made for many years. This Conference puts special emphasis on the various methods used in such comparative work. The Conference theme focuses on methods of hydrological comparison, and deals with both water quantity and quality.

Introduction

This Publication includes 20 papers from western and central Europe. They cover reports from a broad range of current research on hydrologic comparisons carried out in a number of study sites across Europe and using a wide range of methodological approaches.

Each Chapter is presented in the form of a self-contained paper, with its own abstract and reference list, but may also be viewed as a component of this overall Report.

The papers are grouped under broad methodological headings for convenience only: basin studies may involve some or all of the aspects dealt with below.

GENERAL

1) Robinson & Whitehead give a brief history of representative and experimental basins with examples of some of the more influential sites. The main types of experimental design are reviewed. The paper emphasises the need for internal process studies in order to explain the observed changes or differences at the catchment outlet, so that the results may be applied to other areas. The recent tendency to group basins into networks, and the increasing interest in water quality problems are also addressed.

2) Anselmo & Villi provide a cautionary warning about data quality, taking as an example a small basin in Italy for which to compute the annual water balance - the most fundamental of hydrological parameters. Even though snow and wind turbulence problems of the raingauge measurement could be neglected at the site, they showed that other factors could still produce a wide range of possible values of the annual runoff coefficient. Such problems are obviously magnified greatly when hydrologists consider comparisons between basins.

3) Barbet & Givonne describe the ERB Inventory ICARE which contains information on nearly 100 European basins. This provides an invaluable source of information about suitable basins for study.

4) Dean & Marsh review some of the recent UK experience in the development and application of new methods of measuring hydrological variables. This includes the measurement of streamflow using ultrasonic and electromagnetic gauges, the direct measurement of actual evaporation by the eddy correlation technique, and the continuous measurement of soil moisture using a capacitance probe.

BASIN COMPARISONS

5) Molnar describes the methodology being adopted for an ambitious integrated project in the mountainous area of the Slovak Republic, where a range of scientific disciplines are being coordinated in a major multidisciplinary project. Hydrology is seen as a key part of wider environmental studies.

6) Miklanek *et al.* outline some of the findings and some of the problems of working in a harsh mountain area, with pronounced gradients, not just of elevation but also

hydrological variations within a region between mountain and foreland

7) Bicik describes a basin study which at first appears to contradict one of the best researched topics in catchment hydrology, namely that forest cutting may significantly increase water yield. Data for a heavily polluted area in the Czech Republic showed little hydrological effect; this probably reflects the poor state of the trees before they were felled (minimal transpiration and interception). Water chemistry showed significant time trends (related to changing deposition levels and to liming).

8) Cann describes the use of paired catchments and before/after analyses to study the impact of agricultural intensification on nutrient loads. He notes the problems of these two approaches - other catchment differences and weather variability respectively, and emphasises the need for long-term studies for both types of analysis.

9) Fuhrer details a long-term double paired basin study with two control basins and two experimental basins which were clear felled. His study shows the effect of weather variability (despite a ten-year calibration period) and also notes that different conclusions concerning the magnitude of the changes due to felling would be reached using the two different control catchments.

10) Burt & Heathwaite address the scale problem - i.e. how to combine point process measurements inside the basin with the lumped basin outputs. They compared nutrient loadings at different sites within a catchment - from hillslope and field to catchment outlet. Nitrate contributing areas vary with hillslope hollows and riparian zones adjacent to streams.

11) Merot suggests an interesting way to look for order using chemical data: Cl^- is used as a conservative tracer to describe water movement and nitrate as a nutrient loss from an agricultural catchment. This assumes a uniform area with no differences in physical characteristics including land use or fertiliser applications. The relationship between the two chemicals is poor for small areas, but improves for larger areas.

MODEL APPLICATIONS

Lumped Black Box: Here the principle aim is to produce a model with only a few parameters which may be related to catchment characteristics, and so ultimately may be used to synthesise flows from ungauged catchments.

12) Littlewood & Jakeman apply a continuous rainfall-runoff model based on unit hydrograph principles to a number of catchments. The methodology is suitable for detecting trends in a given basin and it is intended that the research will lead towards relating the model parameters to catchment characteristics, in order to be able to apply it to ungauged basins. The model makes no assumptions about physical processes - quick flow might be generated from channel banks, or possibly from overland flow, the origins and processes and chemistry would be different, but their timing might be similar (or indistinguishable).

13) Felice *et al.* use a deliberately very simple monthly rainfall runoff model with minimum data requirements to optimise a single parameter describing the basin storage/geology. They apply this to nine basins of widely different size, and relate results to three categories of geology.

Physically based: Here the aim is not merely to demonstrate that complex multi-parameter models are better at 'curve-fitting' than simpler models, but to apply models with parameters that may be physically interpreted, and so may be used to help predict responses under perhaps different circumstances than those under which the models were calibrated.

14) Babiakova *et al.* compare two basins under similar external effect (acid deposition) and attempt to explain the differences in the basins' outputs in terms of the catchment characteristics. These ideas are then tested by applying a model of the processes of snow accumulation and melt.

15) Gallart *et al.* combine catchment monitoring and a modelling study to compare present catchment conditions with a reconstruction of past conditions, and reach conclusions about the influence of artificial terraces on streamflow.

16) Galea *et al.* apply two rainfall runoff models to a paired basin comparison (similar except for land use differences) and then use these model parameters to study the behaviour under different climatic conditions.

Regional studies

Groups of basins:

17) Blazkova & Kulasova compare the storm runoff coefficients and unit hydrograph parameters for a number of basins in Bohemia, for design flood estimation.

18) Symader made a regional study of water quality related to basin characteristics, using multivariate statistical analysis. The important characteristics varied for different chemical parameters and different landscapes.

Geographical Information Systems techniques:

19) Breinlinger *et al.* use a GIS to classify basins for hydrological regionalisation and estimation in Switzerland.

20) Andersson *et al.* studied N trends over time and found problems in distinguishing short-term variations (e.g. due to forest management activities) and long-term time trends. Different test statistics yielded different conclusions for reasons including their different treatments of extreme values and of serial correlation. They used a GIS to derive catchment characteristics, both static, e.g. soil type, and changing, e.g. areas felled or fertilised.

21) Del Barrio *et al.* use information theory to determine the optimum grid size for DTM work. Where the contour distribution is heterogeneous there is not a single theoretically optimum grid size for a territory. Therefore the method uses a supervised procedure to make an objective choice.

Themes

A number of topics or themes became evident during the course of the Conference, and some of the main ones are described below:

- The uncertainty of measurement accuracy was highlighted (Anselmo) and there are particular problems in mountain areas; there are problems not only with flow and rainfall measurement, but also with extrapolating values from point measurements to basin averages (Miklanek, Molnar).

- Several papers dealing with basin monitoring emphasised the need for long-term studies, not just for studies of time trends, but also to characterise even 'static' conditions such as the calibration period before a catchment manipulation, due to the effect of natural climatic variability (Cann, Fuhrer).

- Several papers note the significant, but not widely recognised, problem that different methods of comparison may lead to different conclusions; Fuhrer noted the difference between two control basins, although both were apparently similar, and Andersson *et al.* found that different test statistics could give different results when examining for time trends.

- Several papers calibrated models and then used them as a means to explore the likely behaviour under different circumstances - including the reconstruction of a past catchment condition (Gallart) and the behaviour under different climate scenarios, in order to try to generalise the findings of a basin comparison (Galea, *et al.*).

- The complexity of basin behaviour was also noted in some papers, and the need to describe catchments and their changing state accurately. This includes the conflicting hydrological effects of forest activities and the interpretation of water quality trends under changing deposition loadings and local amelioration activities of lime application (Robinson & Whitehead, Bicik). The lack of a hydrological effect of forest cutting in one study was possibly due to the poor state of the forest before cutting.

- The problem of scale was dealt with in several papers - different processes may operate at different scales, not just in cases where mountainous headwaters feed into larger lowland catchments (Miklanek), but also at smaller scales e.g. hillslope and valley bottom (Burt & Heathwaite), and even in an unusually uniform area (Merot).

- The application of GIS to regional studies was also demonstrated in a number of papers as a powerful way of handling spatial data that may be hydrologically significant (Breinlinger *et al.*, Andersson *et al.*, Del Barrio *et al.*).

- Several papers used models or statistical relations with parameters that might then be related to catchment characteristics and applied to ungauged basins (Littlewood & Jakeman, Felice *et al.*, Blazkova & Kulasova).

- There is a need to consider embedding short-term investigations within longer-term experiments e.g. transpiration rates from forest before cutting (Bicik), basin leakage studies (Fuhrer), short-term measurements to determine if sampling frequency is adequate (Merot), or studies of flow components in order to be able to extrapolate to other basins with confidence (Littlewood & Jakeman).

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Contents

1. A review of experimental and representative basin studies

M. Robinson & P.G. Whitehead

ABSTRACT

Catchment studies in hydrology are conducted for a wide range of purposes including the need to understand the water balance in basins, the processes controlling water movements and the impacts of land use change on water quantity and quality. Following a summary of the methods adopted, a brief review is given of some of the most influential experiments and their underlying objectives and results. Often, but not always, they have been concerned with land use change. The interactions between physical, chemical and biological behaviour have become an increasingly dominant theme in recent years, and this has been boosted by the global environmental problems such as acid rain and climatic change. The recent tendency to link basin studies into networks is discussed with examples of currently active networks.

INTRODUCTION

The *drainage basin* or *catchment* is a natural unit of study for hydrologists and hydrochemists. Not only is it possible to make a budget between inputs and outputs such as water and chemical loads, but the outputs represent the integration of the processes operating within the basin. This integration is continued in the field of ecology as many ecological systems act according to the stresses imposed by streamflow, chemistry and catchment and climatic factors.

Although human societies have long recognised the importance of precipitation for the needs of plants and crops, only in the last three centuries has it been understood that it is in fact recycled water. Early ideas of streamflow generation were largely based on guesswork and mythology; it was widely thought that rainfall was quite inadequate to account for river flow and that the main source of streamflow was subterranean sources linked in some way to the oceans (Biswas, 1970). It was not until the seventeenth century that plausible theories about the hydrological cycle based on experimental evidence were first put forward. Pierre Perrault and Edme Mariotte measured rainfall and river flow in the Seine basin in northern France and demonstrated that precipitation was far in excess of river flow, contrary to earlier theories of a predominantly subterranean and non pluvial origin. With Edmund Halley, in England, who conducted much pioneering work on evaporation they may be regarded as the founders of modern hydrology (UNESCO/WMO/IAHS, 1974).

EXPERIMENTAL TECHNIQUES

The simplest form of basin study is of a single basin; often one that has been selected as being typical or *representative* of a region, in terms of its attributes such as vegetation type, geology and slope. Such a basin is studied under relatively unchanged natural condition. Alternatively an *experimental* basin may be instrumented to evaluate the effects on hydrological behaviour of changes in land use or land management. A *paired catchment* study may be also used to evaluate the effect of land use. In this approach a comparison may be made between two adjacent catchments which are considered to be similar in all other respects than vegetation cover, and differences between the catchment flows are attributed primarily to the land use. Alternatively, two catchments may be selected which have the same land use. One catchment is left unchanged, to act as a *control* whilst the other catchment has its land use manipulated after a *calibration period* during which a relationship is established between the flows from the two basins. This relationship is then used to provide a comparison with observed flows from the experimental basin after its change. The advantage of the paired catchment approach to a single site comparison, before and after a land use change, is that it enables the effect of climatic variability to be reduced or eliminated.

PIONEER BASIN STUDIES

Investigations into the importance of catchment characteristics, and in particular land use, upon river flows began at the end of the last century. Following a series of disastrous Alpine floods in the 1860s and 1870s it was recognised that investigations were necessary to identify the role played by deforestation if a sound basis were to be given to a policy of reafforestation and rehabilitation of mountain lands. This led to the establishment of the first modern basin study in 1902 in the Emmental region of Switzerland when two catchments, the mainly forested Sperbelgraben and the mostly pasture Rappengraben, were instrumented (Engler, 1919). The catchments are each approximately 0.6 km^2 and have approximately 1650 mm yr^{-1} precipitation. Results indicated that flood flows and annual yields were lower from the forested catchment; baseflows were higher. Although doubts have subsequently been expressed regarding the quality of the data (including the difficulty in accurately measuring snowfall), the principle of the benefits of forest cover in mountainous areas has now become widely accepted (Keller, 1988).

Shortly afterwards, basin studies were established in other countries. Perhaps the best known of these is the Wagon Wheel Gap catchment study in southern Colorado, USA. There, instead of simply directly comparing flows from two basins assumed to be similar in all respects except vegetation cover, a change in land use was imposed on one basin during the study and the other basin was used as a 'control'. The basins were each about 0.9 km^2 in area, with deep, very permeable, coarse textured soils. Almost half of the annual precipitation of 530 mm fell as snow. After an eight-year calibration period the forest in one basin was cut down and the subsequent changes in its streamflow relative to that of the untouched control catchment were ascribed to the removal of the trees (Bates & Henry, 1928). It was concluded that forest removal increased the annual streamflow by approximately 30 mm yr^{-1}, over the following seven years, mostly as higher spring flood discharge, and also as a small increase in summer low flows. The importance of plentiful winter snow and deep permeable soils in these results was stressed.

VERIFICATION, EXTENSION AND PROLIFERATION

Many other basin studies followed thereafter with measurements of precipitation and streamflow. It was reasonably argued that further studies were necessary, since under different site conditions (including climate, topography and soils) different changes could well result from land use change. Possibly the most comprehensive to date study has been conducted at Coweeta in the USA.

Coweeta

The Coweeta catchments in North Carolina have been called the oldest continuously operating catchment study in the world (Swank & Crossley, 1988). The area was selected in the early 1930s as a suitable site for forest impact studies, being a headwater drainage basin about 18 km^2 meeting the requirements of a well developed stream channel system, perennial flow, high rainfall (about 1800 mm yr^{-1}), deep soils (1-2 metres) and a complete forest cover (mainly hardwoods). Catchment experimentation in over 20 subcatchments has included clearfelling and replanting.

The long term streamflow records for the Coweeta catchments provide a means of evaluating hydrological response to different types of forest management. Clearcutting increased mean stormflow and peak flow rates by about 15%. Natural alteration of vegetation by insect defoliation influenced water yield by stimulating leaf production and increasing evaporation, thus reducing winter streamflow by between 7% and 18%. The long-term experiments showed the strong dependence of streamflow volumes on forest type; hardwood to pine conversion reduced annual runoff by 250 mm. Hardwood to grass conversion also altered streamflow, depending on grass productivity, with a decline in grass leading to increased streamflow. The major hydrologic conclusions from Coweeta were that forest managers should recognise that silvicultural prescriptions will affect both transpiration and interception, and hence streamflow.

In the 1960s Coweeta's long records of climate and hydrology proved to be fundamental to environmental studies on the impacts of forest management. University groups undertook studies on ecosystem response and mineral cycling and through the 1970s this programme expanded to assess the effects of site preparation, herbicides and fire on water quality in the Coweeta streams. Acid rain became a major issue in the 1970s and 1980s and Coweeta became a significant site within the National Acid Precipitation Assessment Program (NAPAP), and has provided some of the best baseline data for assessing the impacts of acid deposition on forest ecosystems. Additional studies at Coweeta include vegetation changes, nutrient dynamics, insect diversity, stream biology, trace metals and soil hydrochemical processes (Swank & Crossley, 1988).

Many methods and concepts were adopted from Coweeta in establishing other catchment studies such as the Andrews Experimental Forest in Oregon and the Hubbard Brook experiment in New Hampshire. In the 1950s attention was also given to those developing countries where the impacts of land use changes were most significant. Most notable was a series of experiments in East Africa (Kenya, Tanzania and Uganda) into the effects on water yield and on streamflow of replacing forest by tea estates, pine plantations, grassland and cultivated crops.

East Africa

In 1957 and 1958 four paired catchment studies were established. Three were concerned with the replacement of natural forest vegetation in high rainfall areas and the fourth with restoration methods for semi arid degraded grass savanna (Edwards & Blackie, 1981). Data from the latter experiment was, however, discontinuous due to its remote location and the experiment had to be curtailed.

The three forest studies were on deep permeable volcanic soils, with annual rainfall of about

2000 mm. Measurements included the major components of the hydrological balance and in addition, very importantly for the interpretation of the results, process studies were conducted of evaporation and transpiration, and simple conceptual catchment models were developed and applied.

At Kericho a 5.5 km^2 montane forest catchment was compared with a 7 km^2 basin under tea plantation. Annual flows were somewhat higher from the tea plantation. No differences were detected in the seasonal pattern of flows although process studies, including a lysimeter experiment of the water use of tea, suggested that this conclusion might not hold in other environments.

The Kamakia study compared 0.65 km^2 bamboo forest catchment with 0.36 km^2 pine plantation, and found that once the plantation had reached canopy closure there was no significant difference in annual or seasonal flows.

At Mbeya, the annual streamflow and baseflows from the 0.2 km^2 agricultural catchment (maize) were higher than from the 0.16 km^2 montane forest control catchment. There was little difference in storm response at this or the other sites, and this was very dependent on the very porous nature of the volcanic soils.

International Hydrological Decade

The 1960s was a time of great interest in catchment research, with the initiation of the International Hydrological Decade (IHD) and the establishment of a large number of experimental and representative catchments across the world (see, for example, De Costa & Jacquet, 1965; IAHS, 1965; Toebes & Ouryvaev, 1970). Figure 1 shows the distribution of over 600 representative and experimental basins by latitude at the start of the IHD. By the end of the IHD there were over 3000 of such basins worldwide.

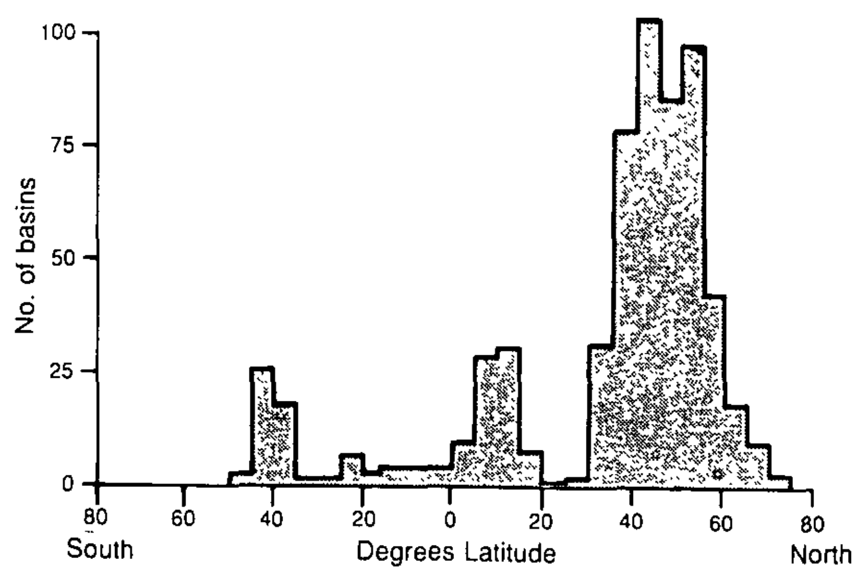

Figure 1 *Global distribution of experimental and representative basins at the start of the International Hydrological Decade*

Rodier & Auvray (1965) describe the establishment of research basins in tropical West Africa, where the main aim was to study the effect of catchment characteristics, including forest, on floods. Such catchment studies have proved to be invaluable for engineering design purposes (floods, reservoir yield calculations etc.) but need to be taken to another stage to provide scientific understanding of the internal processes involved. They have been criticised for their expense, unrepresentativeness, the long calibration period needed and the fact that it was often difficult to interpret their results (e.g. Ackermann, 1966). Although Hewlett *et al.* (1969) argued against many of their criticisms, it is undeniable that the lack of basic process knowledge meant that it was difficult, if not impossible, to extrapolate the results of a basin study to other areas with any confidence.

As an example, the majority of the catchment studies concerned with forestry dealt with the felling of an existing forest, rather than the much longer and more expensive procedure of afforestation. Later research has indicated the importance of the *type* of logging method adopted, with severe ground compaction producing significantly lower soil infiltration capacities hence reducing soil water recharge and the ability to sustain dry weather flows. Infiltration may also be reduced by the replacement land use, perhaps involving overgrazing or the construction of roads and villages (Bruijnzeel, 1990). Consequently it is often very difficult to separate the effect of the tree cover from that of ground disturbance. In afforestation studies the interpretation of the results may be complicated by the need to install artificial drainage channels. Such drainage is generally deeper than the previous natural network of channels and, even accounting for any dewatering of wet soils, tends to enhance dry weather baseflows. The extent to which this effect balances the impact of the growing trees to decrease low flows and the manner in which this changes over time is not well known, and is the subject of active research.

In a recent review of basin studies Bosch (1982) discussed their limitations for planning purposes, citing the variability in results between catchments, and the need for more precise information in relation to predicting the changes in individual components of the streamflow, and for optimising the land use in a catchment (through the selection of tree species, spatial pattern of uses etc.).

THE INCORPORATION OF PROCESS STUDIES

From the late 1960s there was a greater awareness of the need to understand processes and of the wider environmental issues involved; increasingly basin studies have become not simply hydrological but rather take a more holistic approach, covering the wider ecosystem perspective and including water quality, nutrient cycling and biota.

Hubbard Brook

The holistic approach has been well illustrated by the Hubbard Brook study where process studies and a multidisciplinary approach were adopted. The study was established by the US Forest Service in 1955 as a major centre for hydrologic research. The site comprises 32 km^2 in the White Mountain National Forest in Central New Hampshire and was originally covered by unbroken forest of northern hardwoods with spruce and fir at higher altitudes. It has an average annual precipitation of about 1400 mm, with impermeable bedrock, well-defined watershed boundaries, reasonably homogenous geological features, soil types, vegetation and climate.

The major emphasis in the early stages of the Hubbard Brook experiment was to determine the impact of forest land management on water yield, water quality and flood flow rates. An extensive network of stream and rain gauges was established for eight small basins, together with monitoring systems for vegetation, soils and weather.

Much of the annual runoff occurs as spring snowmelt, and one of the early objectives of the Hubbard Brook studies was to seek a forest treatment that would increase flow in summer, when water demands were high, and would decrease or redistribute peak snowmelt runoff, thus reducing spring flood potential. Extensive forest clearance experiments were begun on one subcatchment whilst in a second basin the trees were harvested in 25 metre strips alternating with 50 metre wide uncut strips. These experiments showed that in both cases forest cutting could advantageously alter streamflow (Hornbeck, 1975). Annual streamflow was increased, and most of this was in summer months. The increase in water yield resulting from strip cutting one-third of the trees was less than one third of that from the completely cleared basin, probably in part due to enhanced interception and transpiration losses from the remaining forest bordering the cut strips. There were disadvantages under certain conditions of soil moisture and rainfall since complete forest clearing could increase localised flood flows in summer. Of even greater significance was the deterioration in water quality caused by nutrient leaching and enhanced sediment runoff following clearfelling.

In 1976 Hubbard Brook became a centre of long-term ecological research with the aim of developing a better understanding of the response of hardwood ecosystems to large scale disturbance. Integrated studies of vegetation, soil and stream chemistry and biology, biogeochemical process, hydrological processes, bird and insect studies were initiated. Much of this research is reported in major publications by Bormann *et al.* (1979) and Likens *et al.* (1977, 1985). Such long term records are particularly relevant to studies of climate change and the current interest in issues such as increased nitrogen deposition and critical load assessment.

Following the lead of studies such as Coweeta and Hubbard Brook, and those in East Africa, it became increasingly apparent that an understanding of physical processes was vital if the results of catchment studies were to be capable of extrapolation to other areas, rather than simply be confined to the particular area in which they were carried out. This has led in many ways to a move from fieldwork solely at the basin scale to the integration of small plot studies within catchments, and often linked to the application of physically based models.

Two major European studies in which process investigations were conducted within long-term basin monitoring are Plynlimon in Wales and Hupselse Beck in the Netherlands.

Plynlimon

The Plynlimon catchment study in central Wales (Kirby *et al.*, 1991) was initiated in the late 1960s with a comparison of flows from two adjacent 10 km^2 catchments (one mostly forested, the other under grass). They have a high precipitation (about 2400 mm yr^{-1}) and impermeable bedrock of mudstones and shales. Soils are blanket peats on level areas and podsols on the freer draining slopes. Very significantly a number of field-based studies were embedded into the study to provide the understanding and quantification necessary to model the different processes within the two land uses. As the project matured, interest widened from a concern predominantly with flow *quantities* to include nutrient cycling, acidification, sediments and water quality.

Annual evaporation losses were consistently higher from the forested catchment, and the most important process accounting for this was the interception of precipitation by the tree canopy and its faster rate of evaporation than from the aerodynamically smoother grassland surfaces (Calder, 1990). Flood peaks from the forested catchment were lower than from the grassland for small events, whilst for large events there was no significant difference. Dry weather baseflows were dominated by geology and did not differ with surface vegetation cover. Figure 2 shows the annual losses from the two catchments, demonstrating the higher evaporation from the forested basin, but also showing in both cases a downward long-term time trend which has yet to be fully explained, although climate is thought to be the primary cause. This finding helps to emphasise the necessity of such studies to be continued for long periods, so as to encompass a wide range of climatic variability.

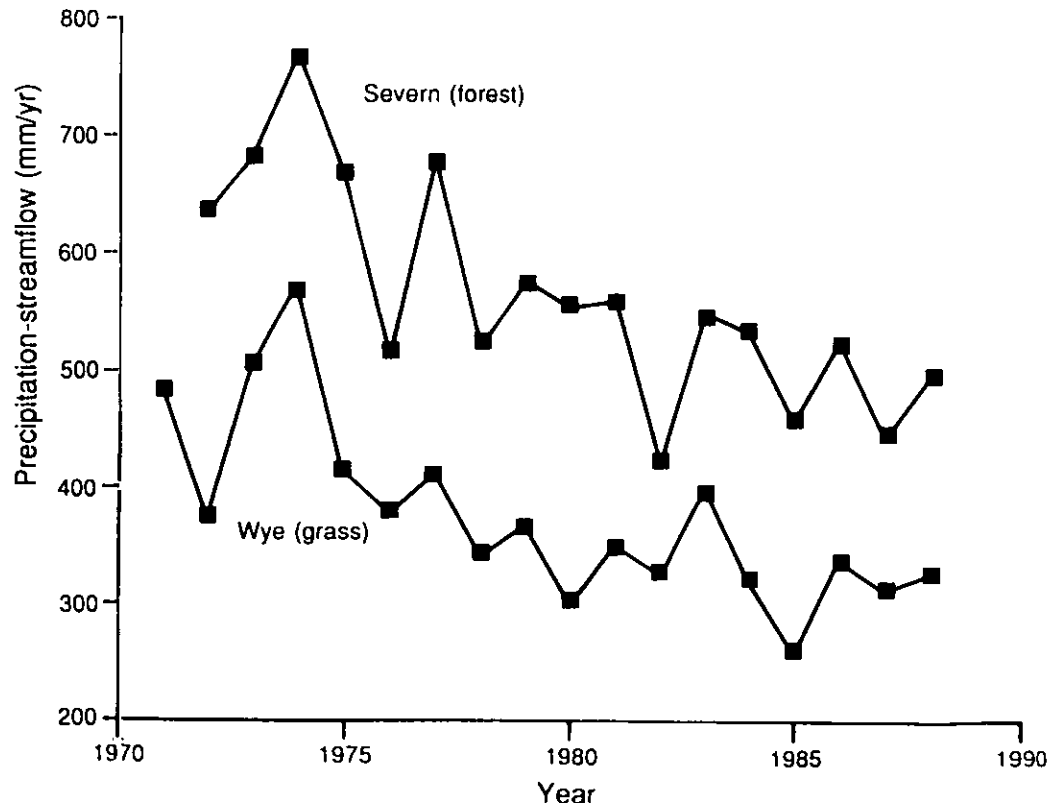

Figure 2 *Annual water use in the Plynlimon catchments, Wales*

Hupselse Beek

This 6.5 km^2 basin was first instrumented in 1962, and work has intensified since 1968 when it was artificially drained for agriculture (Warmerdam *et al.*, 1982). It is considered representative of much of the reclaimed, originally swampy, areas of the surrounding eastern parts of the Netherlands. It has permeable soils developed on coarse sands and gravel overlying impermeable marine clay at depths of 1 - 8 metres, which ensure no deep seepage into or from the basin.

In addition to measurements of the main elements of the water balance, comparisons have been made of flows before and after drainage, as well as studies including micrometeorology, water movement in the unsaturated zone and the transport of nutrients. Its detailed and long-term records have also been used in assessing the impact of climatic change.

CATCHMENT NETWORKS

The value of the results from individual studies may be enhanced by comparing them with those from other experiments. For example the key findings of a number of basin studies are summarised in Table 1. There is a broad degree of uniformity, under a wide range of climatic and topographic conditions, with regard to the effect of forestry on annual flows, but less consensus for extreme flows. A reduction in annual discharge under forestry has been widely reported and the only exception here (Coalburn) has immature plantation trees, and its outflows are dominated by the extensive preplanting artificial drainage (enhancing baseflows) and not yet by the growing trees. The Table also shows peak flows are generally lowered by forest (although its effect on extremely large floods is not so clear) with exceptions due to forestry drainage (Coalburn) and additional physical difference between the paired basins (Plynlimon). Low flows show more variability in results, with a small majority of the experiments indicating forestry reduces baseflows. Those cases where baseflows were higher under forestry may perhaps result from other catchment differences (Emmental), ground disturbance due to logging (Wagon Wheel Gap) and forestry drainage (Coalburn).

Table 1 *Simplified summary of main hydrological effects of forestry from basin experiments*

Site	Principal type of Study*	Streamflow changes due to forest [Decrease (↓), Increase (↑), No difference (n.d.)]			References
		Annual	Peaks	Baseflow	
Emmental	C	↓	↓	↑	Engler, 1919
Wagon Wheel Gap	D	↓	↓	↓	Bates and Henry, 1928
Coweeta	D	↓	↓	↓	Swank & Crossley, 1988
Hubbard Brook	D	↓	↓	↓	Hornbeck *et al.*, 1970
Plynlimon	C	↓	n.d.	n.d.	Kirby *et al.*, 1991
H.L. Andrews	D	↓	↓	↓	Rothacher,1970
Coalburn	A	↑	↑	↑	Robinson, 1986

*Afforestation (A), Deforestation (D), Comparison between catchments (C)

A developing trend since the 1970s has been the combination of data from a number of catchments having different characteristics (slopes, soils etc.) to study the effect of these differences. This has led to the formation of networks of basins whereby information may be transferred and compared. These may be either specially instrumented and maintained stations, such as the network of long-term Benchmark stations operated by the US Geological survey, or more informal networks utilising existing data assembled from a wide variety of sources that had been collected for different purposes and brought together for a particular study. Examples of such *ad hoc* networks are the basins selected for use in the UK's Flood Studies Report (NERC, 1975), and the 1600 northwestern European basins from 13 countries used in the FREND project (Gustard *et al.*, 1989) which aimed to study natural and manmade changes in hydrological regimes. In addition there are networks such as the Experimental and Representative Basins (ERB) network which, whilst using existing gauged catchments, provide a means of increasing contacts between research teams through data exchanges and meetings as well as joint operations of common interest. Figure 3 shows the location of the ERB sites, and details of the Inventory of these sites is given in Barbet & Givonne (1993).

Figure 3 *Distribution of the study sites within the Experimental and Representative Basin Network in July 1992*

Two recently established networks reflect the growing interest in hydrochemical behaviour and ecosystem response to change. These are the ENCORE network (European Network of Catchments Organised for Research on Ecosystems) and the IMP (Integrated Monitoring Programme) network.

CONCLUSIONS

Basin investigations have evolved significantly and become more sophisticated with multiple basins and catchment manipulation, as well as within-basin process studies. There is now considerably more emphasis on the aspects of environmental change as it is recognised that catchment studies offer the means to monitor and detect change. The complex interactions between hydrology, chemistry and ecology ensure that process studies will remain a vital element of catchment studies, with basin outputs providing an integration of within site processes. The development of sophisticated instrumentation techniques (both in the field and the laboratory) have made possible new approaches to problems and increased the type and volume of data that can be collected, but also increased the costs of basin experiments. Many experiments were unable to withstand these cost increases once their initial aims were felt to have been achieved, and, together with the notion that long-term monitoring was 'unfashionable' resulted in the closure of a number of sites. The growing awareness of the problems including transboundary air pollution, acid rain, nutrient, organics, and climate change, means that catchment studies and long-term monitoring have become a high priority, being the primary indicator of global environmental change.

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2. Accuracy of hydrological measurements in instrumented catchments: a case study

V. Anselmo & V. Villi

ABSTRACT

The accuracy of the estimation of runoff/precipitation ratio in a small alpine catchment was checked on a set of one-year of daily data.

The accuracy of flow measurement was derived through the analysis of sources of error (both systematic and random) related to the discharge measurement structure (a compound weir). The uncertainty in precipitation measurement was assessed by means of experimental results reported in literature concerning the influence of wind on precipitation catch.

INTRODUCTION

Instrumented catchments are commonly used as a reference for the assessment of the magnitude of a number of hydrological processes. The degree of knowledge about a process is far most satisfactory if observations derived from different catchments can be compared[1]. The evaluation of the accuracy of measurements may be of primary interest, because the effort to improve instruments and increase the detail of the information requires that attention is paid to the overall accuracy of the data.

From the general point of view, the Italian standard UNI 4546 stresses the fact that the result of a measurement must be expressed with three attributes: the value, the accuracy[2], and the unit of measurement. The accuracy is usually expressed by means of the lower and upper limit of confidence encompassing the 95% of the values likely to be assumed by the measured quantity.

In the field of hydrological measurements, ISO standards as well as ILRI publications on discharge measurement structures include detailed guidance for the computation of the overall accuracy; WMO's publications underline the sources of errors in measurements; Sevruk (1982) offers a keen analysis of methods for correction of errors in the measurement of precipitation, and Herschy (1985) summarizes streamflow measurement methods and devices.

Hydrologists are well aware of the factors due to natural processes as well as to inadequacy of instrumentation that affect the final result of observations.

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[1]I think that what, perhaps, has been wrong with our science and what, perhaps, has inhibited its discovery over the past forty years, is a deficiency in our empiricism, combined with a tolerance of very poor observations. In the field of catchment hydrology we have rarely sought any degree of universality, but have contented ourselves with *ad hoc* investigations often on a single catchment (Nash, 1988).

[2]It is worth noting the oddness of the fact that "accuracy" has in Italian the meaning of "precision" in English, and vice versa. Using the term "uncertainty" could avoid any misunderstanding.

The following analysis is focused on the evaluation of the accuracy of the runoff/precipitation ratio in a small catchment, the Torrente Missiaga located in the Eastern Alps of Italy. The computation is carried out on the data of one year of record, and the main physiographic characteristics are summarized in Table 1.

Table 1 Physiographic characteristics of the catchment

Catchment name	Torrente Missiaga
Area (km^2)	4.4
Max elevation (m)	2547.
Min elevation (m)	1100.
Average altitude (m)	1721.
Talweg length (km)	3.26
Mean slope of sides	.68
Mean slope of talweg	.32
Average annual precipitation in the region (mm)	1300.

Instrumentation details are listed in Table 2.

Table 2 Characteristics of the instrumentation used to assess the runoff/precipitation ratio

Station : Malga Rova	Elevation : 1452 m	
Precipitation	Tipping-bucket recording gauge with gas heating of the funnel. Continuous record on chart moving at a speed of 12.5 mm/h.	The rim of the funnel is 3 m above the ground. No shield is provided. 1000 cm^2 orifice
Wind	Continuous record on chart moving at 10 mm/h. Wind speed and direction recorded on the same diagram.	Sensors are at about 5 m above the ground.

Station : Castellet	Elevation : 1452 m
Water level gauge	Floating type stage recorder. Records are on chart moving at a rate of 10 mm/h. Reduction ratio: 1:5

The instrumentation used in this study is the same as that widely used in Italy by the National Hydrologic Agency (SIMI); so results of the observations are comparable with those of the official stations. The analysis herein summarized was performed on hourly data derived from records of precipitation, wind speed and water stage over the period November 1, 1988 - October 31, 1989. Snow was not important during this period.

It must be recognised that setting up instrumentation in alpine catchments may face some constraints (accessibility, land property, etc.) which prevent a full development of the research (for instance, the role of exposition in rainfall catch). On the other hand, investigations in small catchments are the first step for the assessment of hydrologic processes.

PRECIPITATION

It is widely supposed that measuring rainfall is a simple task. On the other hand, snowfall is recognised as being much more difficult to measure, while dew, hail and like phenomena are very rarely gauged (Rodda, 1971). Investigations on and comparisons of precipitation gauges have been reported since the 18th century (Sevruk, 1982); results point out that the influence of wind and hence elevation above the ground was recognised as responsible for underestimation. A ground level gauge (pit-gauge) was first mentioned in 1812 and at present it is recommended as a reference gauge.

The influence of the number of gauges on the average catch of a basin was pointed out in several studies. Investigations led to depth-area curves for given durations, strongly dependent on the character of the rain events and ultimately on meso-scale circulation. Several authors proposed depth-area curves on the basis of the observed precipitation on areas of different size (Court, 1961); Italian contributions are related to plain areas of direct interest to urban drainage (Columbo, 1960; Bixio and Rolla, 1978; Bertola, 1978). Cappus (1958) presented the results of five years of rainfall records at 11 sites in a 3.1 km^2 catchment exposed to strong winds and showed the maximum deviation from the average according to the number of operating gauges. Considering only one gauge operating in the catchment, with reference to the daily amount of rainfall, the range of the deviation from the average was from 50% to 6% for total depths of 2 and 50 mm respectively. The gentle topography, ranging from 770 to 960 m, proved to be ineffective on the variability of precipitation if compared with the effect of wind. The increase of seasonal amounts of precipitation with altitude was showed by Sevruk (1989) in a 14 km^2 basin with elevation between 500 and 2000 m.

The Missiaga study basin used in this paper is a left tributary of the River Cordevole whose catchment in oriented from North to South. Precipitation is higher on the western side of the Cordevole where a preliminary analysis of atmosphere circulation showed that rainy events are more frequent and abundant (Borghi, 1987). No detailed investigation on the role of elevation is available on the Southern Alps, even if evidence, just in the Cordevole basin (Gatto *et al.*, 1984), can be found of decreasing annual precipitation with increasing elevation.

In the Missiaga basin the runoff/precipitation ratio was computed assuming the depth of precipitation recorded by the raingauge at Malga Rova (1452 m).

The accuracy of the measurement was determined by analysing the sources of errors both random (wind) and systematic (rainfall intensity, raingauge rim not level) assuming that periodic checks of the response of the device are performed. The lack of pollution in the basin prevents the problems typically related to the ageing of the device.

Precipitation hourly data were corrected in dependence on the average hourly speed of the wind according to Table 3. Wind velocity measurements show the distribution presented in Figure 1; most of the rainy hours are characterized by very low wind speed (the maximum value was 12.6 km/h). That is a proof that wind may not be considered a major source of error in the investigated area.

Table 3 *Relationship between wind speed and raingauge catch (Hydrology Centre, 1988)*

Wind speed (km/h)	Raingauge catch reduced by: (%)
0	0
10	8
20	21
30	32
40	41
60	47
80	50

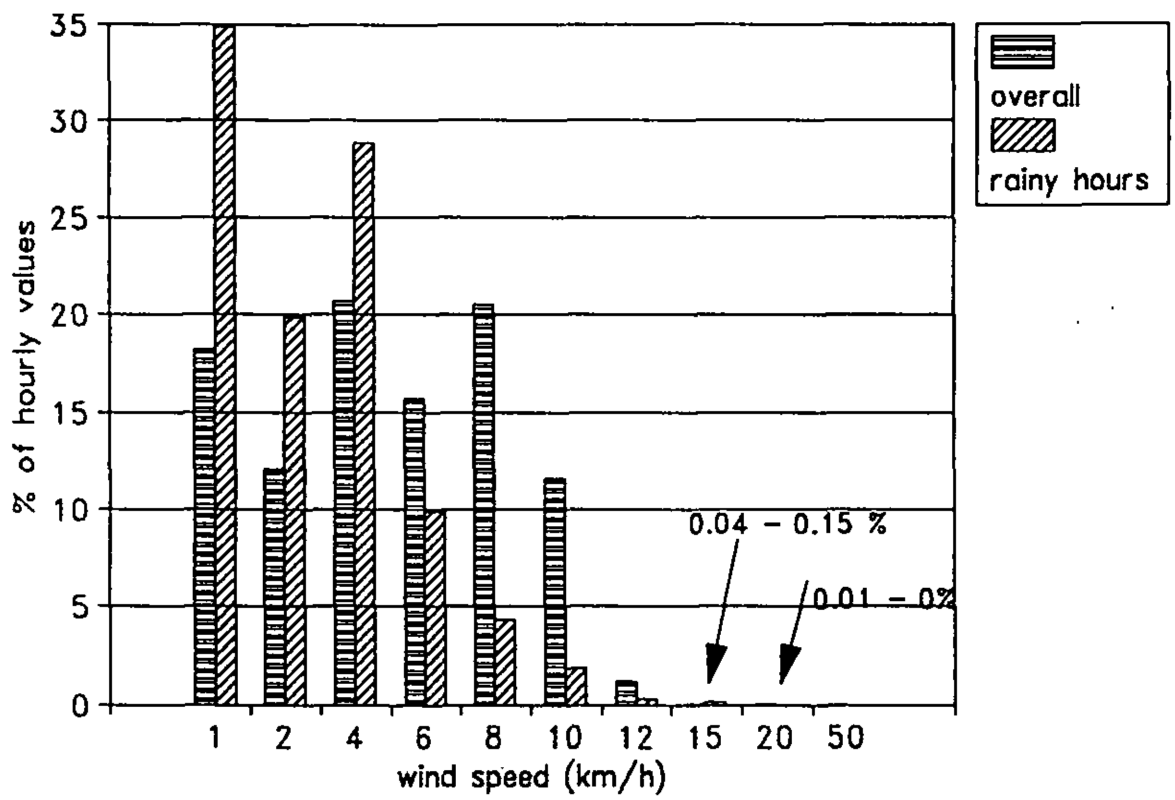

Figure 1 *Frequency distribution of mean hourly velocity (km/hour) at Malga Rova. Values are the upper limits of the classes.*

A further contribution on the topic is due to Cernesson and Lavabre (1989) who studied the influence of the wind speed on the catch of different types of raingauges. They presented a graph expressing the underestimation versus rainfall intensity and wind speed. Rainfall depth and wind velocity were measured at 6 min time steps. The data in this paper are limited to hourly amounts of rainfall and hourly mean wind velocity.

The accuracy of the tipping bucket raingauge decreases with increasing rainfall intensity. A few contributions (Enel, 1969; Becchi, 1971) showed that underestimation depends on the type of the device, but it is below 3% for intensities up to 40 mm/h; then it increases rapidly up to 5-10% for intensities of 60-120 mm/h. More recent devices show better performances (for example, 0.5% for intensities up to 50 mm/h; Regione Veneto, 1985). Since automatic processing of data is more and more easy, it is advisable to check each device in order to apply its proper correction curve.

Out-of-levelness of the orifice of the gauge was showed to affect the measurement (Sevruk, 1984); the amount of error depends on the aspect and on the angle of incidence of precipitation. Moreover the inclination of the tipping-bucket device, with respect to the axis of rotation of the buckets, may induce underestimation up to 10% for a rotation of 5° about the axis of the tipping buckets (Da Deppo, 1977).

RUNOFF

Water stage is measured at the Castellet station by means of a compound triangular weir: a sharp crested 90° notch and 1:2 sloping side concrete crests. The structure was built above a previous check dam, so downstream flow is free at every condition of discharge.

The computation of the accuracy in stage and hence discharge measurement was performed according to ISO 1438 and Herschy (1985).

When head is below 0.5 m, the flow is confined within the V-notch-sharp-crested weir and the stage-discharge relationship (ILRI, 1989) is

$$Q = C_e \frac{8}{15}\sqrt{2g}\tan\frac{\alpha}{2}h_1^{2.5} \qquad (1)$$

The sources of uncertainty are:

- triangle opening ($X_{\tan\alpha/2}$); the uncertainty is evaluated introducing the errors in the measurement of top width (E_b') and depth of the notch (E_h'). Then

$$\tan\frac{\alpha}{2} = \frac{\text{½ top width of notch}}{\text{height of notch}} \qquad (2)$$

so introducing relative errors

$$X_{\tan\alpha/2} = \pm\left(X'^2_b + X'^2_h\right)^{1/2} = \pm\left[\left(\frac{E_b}{b'}\right)^2 + \left(\frac{E_h}{h'}\right)^2\right]^{1/2} \tag{3}$$

Assuming $E'_b = \pm\ 0.001$ m and $E'_h = \pm\ 0.001$ m, b' = 1 m and h' = 0.5 m

$$X_{\tan\alpha/2} = \pm 100\left[\left(\frac{0.001}{1}\right)^2 + \left(\frac{0.001}{0.5}\right)^2\right]^{1/2} = 0.22 \tag{4}$$

- the uncertainty in discharge coefficient C_e

According to ILRI (1989) the accuracy is expected to be $X_C = \pm 1\%$.

The uncertainty in zero-setting depends on the accuracy of levelling procedure to determine the exact elevation of the crest of the weir and on the internal friction of the recorder. A value of $E_z = \pm 0.005$ m is assumed

- the uncertainty in the reading of stage by means of the floating type recorder. It depends on different sources of error summarized in the overall accuracy stated by the producer. ILRI (1989) cautions about the optimism of manufacturers who usually refer to factory-new recorders. The recorder shows an overall accuracy of $E_g = \pm 1$ cm.

- the uncertainty in manual reading the recorder diagram. Reading is done with $E_R = \pm 0.5$ cm.

The overall uncertainty on the stage reading is therefore

$$X_h = \pm\frac{100}{h}(E_s^2 + E_z^2 + E_R^2)^{1/2} \tag{5}$$

and the uncertainty in discharge evaluation, according to the error combination procedure (it is assumed at 95 % of confidence), is expressed in per cent:

$$X_Q + (X^2_{\tan\alpha/2} + X_c^2 + 2.5^2 X_h^2)^{1/2} \tag{6}$$

The larger opening of the measurement structure was designed according to the scheme of short-crested V-notch weir sill (ILRI, 1989) and data of U.S. Soil Conservation Service (referred in ILRI, 1989) were assumed. The head-discharge equation is now

$$Q = C_d C_v \frac{16}{25}\sqrt{\frac{2}{5}\,g}\ \tan\frac{\alpha}{2} h_1^{2.5} \tag{7}$$

According to what has been stated:

- the accuracy on the opening angle is deduced from the accuracy of width and depth measurements. In this case $E'_h = 0.01$ m and $E'_b = 0.01$ m are assumed. Hence

$$X_{\tan\alpha/2} = \pm 100 \left[\left[\frac{0.01}{3.8} \right]^2 + \left[\frac{0.01}{1.9} \right]^2 \right]^{½} = 0.37 \qquad (8)$$

- The overall uncertainty is evaluated according to the error combination procedure.
- the uncertainty on the discharge coefficient is assumed to be $X_C = \pm 3\%$.

CONCLUSIONS

The results of the computations point out that the uncertainty on the annual streamflow is ±8%; the correction of the precipitation shows an increase of 3% according the correction coefficient listed in Table 3 (Hydrologic Centre, 1988). The correction coefficients proposed by Cernesson and Lavabre (1989) would lead to an underestimation of 12%. This is evidence of the actual need for standardization of testing and correction procedures.

Dividing the lower and upper estimates of flow by the corrected precipitation depth, the annual runoff coefficient assumes a value in the range 0.43 - 0.52 with the first type of correction of rainfall depth, 0.40 - 0.47 with the second one. If both flow and precipitation are not corrected, the runoff/precipitation ratio would be 0.49.

The runoff coefficient is generally assumed to characterize the global hydrologic behaviour of the catchments. Traditionally the Italian National Hydrologic Agency (SIMI) supplied detailed information on rainfall/precipitation rate of more then two hundred catchments as a basis for water resources management.

The tentative analysis presented here outlines the relevance of investigating the range of accuracy of flow measurement. Moreover further research is needed, in an alpine environment, on the spatial distribution of rainfall on large catchments before comparing results.

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3. Introduction to the ERB inventory (ICARE): Inventory of Catchments for Research in Europe

D. Barbet & P. Givonne

SHORT REVIEW OF THE ERB-INVENTORY HISTORY

In October 1986 the French inventory of representative and experimental research basins was presented during the first General Assembly of the European Research Basins Network at Aix-en-Provence (France). Originally, this inventory was developed in collaboration with the French Ministry of Research and Technology, in order to guide their national policy towards research basins.

At first, the computerisation of the French national inventory was developed by CEMAGREF LYON on a VAX 750 computer, with DATATRIEVE as the file manager and query language.

Considering the usefulness of the French Inventory, some European researchers at the Second ERB Conference at Perugia in 1988 proposed an extension of this to an Euro-Mediterranean scale. In answer to the needs of this expansion, it was necessary to switch to a more practical tool in terms of:

- the possibility of decentralisation,
- greater flexibility of the database structure,
- easier retrieval and updating of data,
- better intelligibility of the data.

In December 1989 the computerization of a new relational ERB-inventory was started, using OS/2 software with an integrated Relational Database System DBM, implemented on a PS/2 (IBM PC 386). The implementation on a standard micro-computer makes it exchangeable and compatible between different laboratories in Europe. The relational structure of the database makes updating easier and will facilitate adaptations to future needs. The use of a standard query language (SQL - Structured Query Language) makes it also manageable on a centralized site, with the possibility of consultation via networks (e.g. EARN-BITNETT).

OBJECTIVES OF THE ERB-INVENTORY

The main objectives of a computerized inventory of 'EUROPEAN RESEARCH BASINS' are:

(a) to inform hydrologists (or other scientists) and managers about existing research basins, and provide information about their location, research objectives, project managers, recorded data, equipment, hydrological, geomorphological and climatological characteristics,

(b) to validate some data sets from European research basins, in order to test and to compare different hydrological models,

(c) to gather general data which are often dispersed over different laboratories.

This inventory has a descriptive character and it is not intended to compete with bibliographic or numeric databases, although a future development in that direction is not excluded if, and only if, wanted by the providers of the information.

STRUCTURE AND CONTENT OF THE ERB-DATABASE

The ERB Inventory is held on a relational database. Considering the objectives of the ERB-Inventory, one of the main questions to answer before starting up the database is: what sort of information is needed to give a good description of the basins and how can this information be structured? Analysis of the problem led to the establishment of 11 types of information ('entities') and 77 'attributes':

1) ENTITY ERB

General information about the basin: The attributes are:

- *Name of basin*
- *Main objective*: the research aims of the basin
- *Climate* classification
- *Thornthwaite index*, gives a classification of the climate based on the relation between water supply and water losses due to evaporation under the influence of a given climate. The index is based upon four criteria:
    - moisture index of global humidity index
    - seasonal variation of the effective humidity
    - thermal efficiency index
    - thermal efficiency during the three summer months
- *Closing date* of the basin, if no longer operating.

2) ENTITY OBJECTIVE

- *Standardized objective*: classification of the detailed objectives into one of the main research domains of hydrology or hydraulics.
- *Detailed objective*: objective of the various research projects conducted on the basin.
- *Project manager*: the Laboratory responsible for the scientific management of the research project(s).
- *Telephone number* of the project manager.
- *International telephone code*
- *Address of the project manager*
- *Electronic address of the project manager*
- *Research period*
- *Model data set*: set of data recorded during a research project with the aim to test, validate and compare hydrological models.
- *Title of one reference publication.*

- *Author(s) of publication.*
- *Year of publication.*

3) ENTITY ADMINISTRATION

- *Administrative manager*: Laboratory or institute responsible for the administration of the basin.
- *Telephone number of the administrative manager*
- *Address of the administrative manager*
- *Electronic address of the administrative manager*
- *Investment*: money available for the management of the basin.
- *Currency* in which the money is expressed. (in MEGA).
- *Permanent agent*: number of full time staff in charge of the basin.

4) ENTITY STATION

This distinguishes two types of stations, namely stations related to an area, i.e. hydrometric stations, and stations related to a place, i.e. raingauge stations.

- *Name of station*
- *Altitude of station*
- *Surface*: the area controlled by a station; for hydrometric stations this is the area of the catchment. For a 'point' station this is equal to zero.
- *Relative position* of a station in relation with the general structure of the ERB, or position of the equipment in case of a station related to a place.

5) ENTITY CHEMICAL/BIOCHEMICAL DATA

- *Nutrient*: set of observed nutrients
- *Physical parameter*: (temperature, conductivity...)
- *Biological parameter*: (COD, BOD....)
- *Cation*
- *Anion*
- *Heavy metal*
- *pesticide*
- *miscellaneous*

6) ENTITY RECORDED DATA

- *Recorded data*
- *Minimal time* step of data available.
- *Continuity*: are the data series continuous or do they show (important) gaps?
- *Evaluation of the data*: general qualitative evaluation of the data sets.
- *Starting date*: year from which the data are available.
- *Ending date* of the available data.
- *Record-class*: classification of the type of data through a fixed lexicon (discharges, rainfalls, temperatures,...)

7) ENTITY EQUIPMENT

- *Type of equipment*
- *Mark of equipment* or a characteristic of the equipment.
- *Minimal time* step of recording (day).
- *Continuity* of recording, Flag: Y(es) or N(o).
- *Starting date*
- *Ending date*

8) ENTITY HYDROLOGY

- *TA*: mean annual temperature (°C).
- *PA*: mean annual precipitation (mm).
- *QA*: mean annual discharge (mm).
- *DXPY10*: daily maximum precipitation with a return period of 10 years (mm).
- *QB/QA*: rate of baseflow and total runoff on a yearly time basis.
- *QTSA/QA*: rate of sediment (mass) discharge and total discharge (volume) on a yearly time basis (kg/m^3).

9) ENTITY GEOMORPHOLOGY

- *Maximum* altitude of the (sub)basin related to a station (m).
- *Minimum* altitude (m).
- Percentage of *impervious* area in the basin.
- Percentage of *pervious* area.
- *Maximum length* of the thalweg (km).

10) ENTITY LANDUSE

- Percentage of the basin occupied by forests.
- Permanent vegetation (%).
- Annual vegetation (%).
- Urbanised surfaces (%).
- Lakes (%).
- Humid zones (%).
- Glaciers (%).
- Mineral soils (%).

11) ENTITY UPDATING

This entity is added to inform the user of the latest updating of the database or a part of the database.

- *Updated* entity.
- Date of *updating*.

This is the information stored on the ERB-database. The entities group attributes are more or less related to one another through the semantics of the data.

CREATION OF THE RELATIONAL DATABASE

Software

For this project we chose for a Database Manager Programming Interface: DBM, that runs in the OS/2 mode (the multiplexing mode) of the IBM Operating System /2 Extended Edition program.

The database manager provides data definition, retrieval, update and control operations through SQL (= Structured Query Language). SQL is a high-level data language available to users interactively through Query Manager or through application programs using Database Services.

Query Manager is a menu-driven interface that provides interactive access to data for data entry, data edit, query and report development through the SQL language. Query Manager provides application creation tools for using display panels, menus and procedures, enabling the user to develop database applications without the need for programming.

Database Services provides the various facilities to create and maintain a database. The programming interface to Database Services is through SQL statements and function calls embedded in an application program.

The Entity - Association Model

If we examine the entities more closely we notice that entities such as ERB, OBJECTIVE, ADMINISTRATION, UPDATING and STATION are related to a research *basin*. The entities STATION, DATA, EQUIPMENT, HYDROLOGY, GEOMORPHOLOGY and LAND USE are related to a *station*. STATION forms the junction between those two groups.

The relation between ERB and STATION, the two basic entities, and all other entities are achieved by the use of 'keys'. We therefore introduce two 'key' - attributes:

- *Code of basin*: the code consists of 8 characters, the first 3 indicate that it concerns a European research basin (ERB); the next 2 characters are the abbreviation of the name of the country according to the ECC-standards; the last 3 are numbers. For instance a code of a French basin could be ERBFR001.

- *Code of station*: the French stations have an 8 character code, depending on whether it concerns a 'surface' station or a 'place' station.

'Code of basin' and 'code of station' are both so-called primary keys, besides them we have access keys and foreign keys . Other keys essentially required, are: name of basin, detailed objective, standardized objective, code administrative manager, name of station, record, equipment.

In 1989, 17 French basins were chosen on the basis of their completeness and variety of data, to test the relational database. With the OS/2 editor, the data of these basins were rearranged

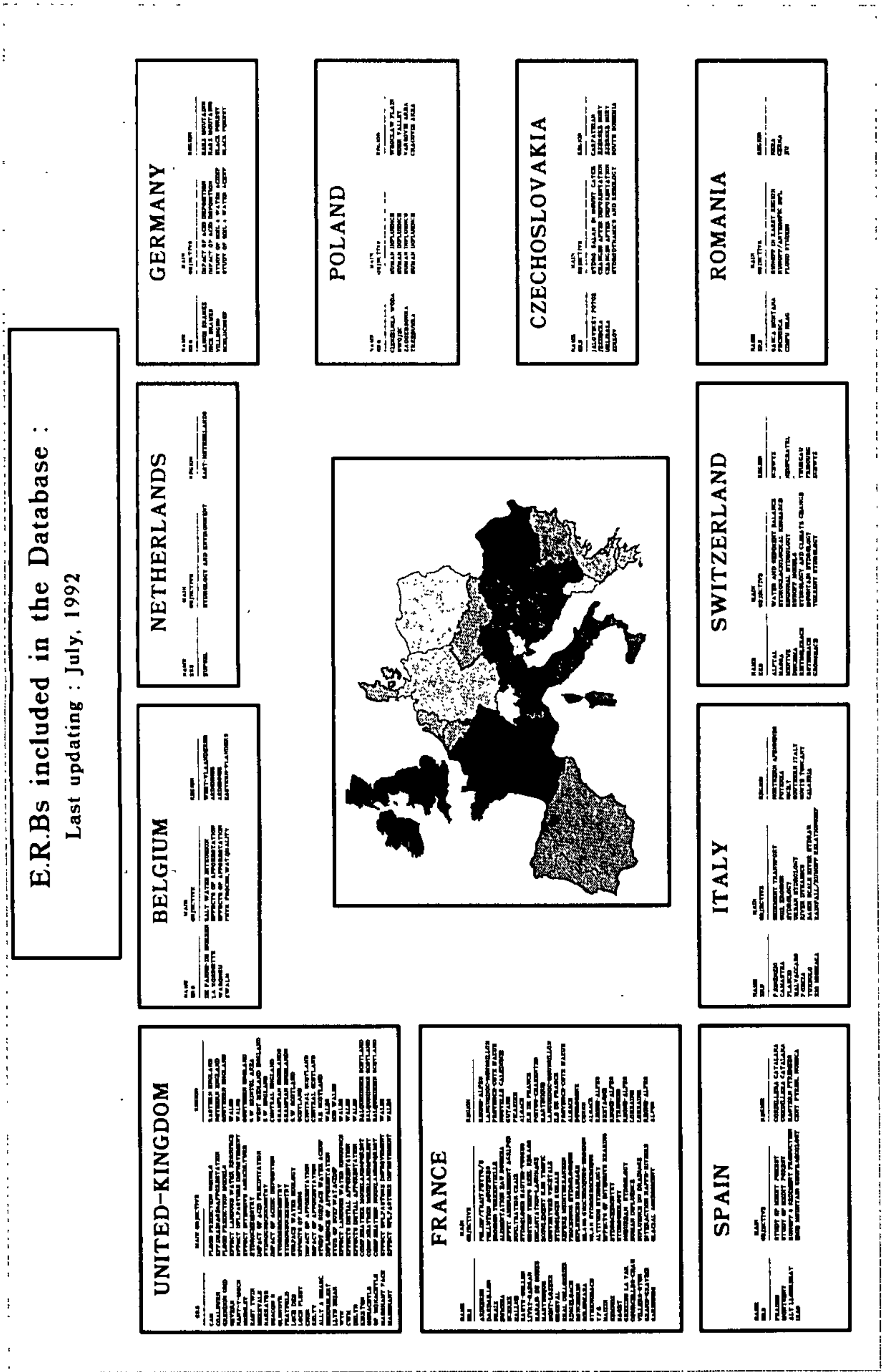

Figure 1 *Basins included in the ERB inventory*

and made more coherent, so that direct importation in the tables was possible. Eight English and five Italian basins were added afterwards as also two basins in Switzerland and Belgium and one basin in the Netherlands. At present 92 basins are stored in the E.R.B. database.

SPAIN	(ERBES)	:	4	ERBs
ITALY	(ERBIT)	:	8	ERBs
SWITZERLAND	(ERBCH)	:	7	ERBs
CZECHOSLOVAKIA	(ERBCZ)	:	4	ERBs
POLAND	(ERBPL)	:	4	ERBs
ROMANIA	(ERBRO)	:	3	ERBs
GERMANY	(ERBDE)	:	4	ERBs
NETHERLANDS	(ERBNL)	:	1	ERB
BELGIUM	(ERBBE)	:	4	ERBs
U.K.	(ERBGB)	:	27	ERBs
FRANCE	(ERBFR)	:	26	ERBs
TOTAL		:	**92**	**ERBs**

These basins are listed for each member country in Figure 1, and the ERB network is summarised by the objectives of these basin studies in Figure 2.

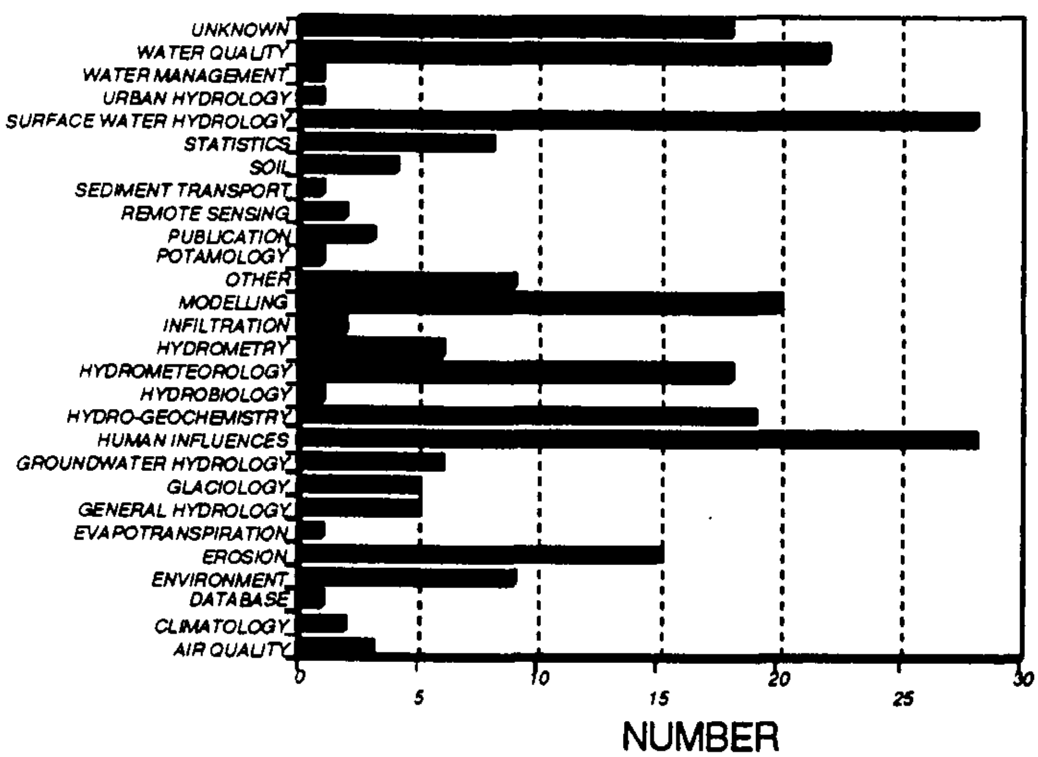

Figure 2 *Number of ERBs in the Inventory classified by their research objective(s)*

FUTURE DEVELOPMENT

The further development of the ERB database depends on decisions about its future management and finance, and this is directly related to the future of the ERB Network.

If it is decided to leave the ERB inventory as it is now, because of lack of financial resources or lack of interest, the database will be transferred to the different laboratories, by means of a copy of the ERB database, PC version. Each laboratory can develop it the way it is most suited to the own activities. Consequently, this means that the ERB data network will be broken up.

At the other hand, it is preferred to keep the ERB database centralised, but with the opportunity of consultation by all laboratories, the database will be connected to the EARN - BITNETT network. This option, however, is more expensive and requires concurrency control to maintain data integrity. The access of more than one program to the same data at essentially the same time must be controlled to prevent effects such as lost updates, access to uncommitted data and unrepeatable reads.

Another important problem, not yet tackled, is the management of privileged access. The Database Manager provides commands to control the means of access of the different users: access for creating and updating the database and access only for consulting.

The database can evolve towards the implementation of numeric data. In a first stage the so-called 'Model Data Sets' could be integrated, later on even long series of data. By writing OS/2 application programs, the desired data can be retrieved by means of embedded SQL statements, and processed immediately. The fact that the use of the ERB database is not limited to withdrawal of data only, but that the data serve directly as input for an application, gives this tool a more dynamical aspect.

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4. Recent technical developments in the measurement of hydrological variables

T.J. Dean & T.J. Marsh

ABSTRACT

Some recent developments in measuring components of the hydrological cycle are summarised with particular reference to the research and development work carried out in the United Kingdom.

INTRODUCTION

Hydrology, as an environmental science, is particularly dependent on observed and recorded data, which in turn require precise and reliable instrumentation. This may be an individual, portable, instrument or a complete system, usually automatic, comprising a sensor, or an array of sensors, interfaced to a logging unit. The environmental conditions encountered in the UK are less challenging than those found in many parts of the world. However, the need for accurate data to improve both our understanding of hydrological processes and to contribute towards the development of more effective water management procedures, provides a continuing stimulus to extend the range of practical options for hydrological monitoring and measurement.

DATA LOGGERS

Data loggers can do much more than simply record data from a modern sensor array; they may control additional equipment such as a stream sampler and can be programmed to adapt to particular situations. For example the user many need data only after rainfall greater than a certain intensity and while soil water content is above a particular threshold.

Good operational practice requires regular periodic visits to check the status of equipment and usually this opportunity is taken to retrieve stored data. This operation takes a matter of seconds or minutes and has proved in practice to be extremely reliable regardless of the location and weather conditions. It is often desirable to telemeter data directly from the field, particularly for remote sites. For example, in the Anglo-Brazilian Amazonian Climate Observational Study (ABRACOS) project in Brazil seven Automatic Weather Stations (AWS) have been interfaced to a Data Collection Platform (DCP) transmitter. Telemetry of hourly meteorological data is via the Meteosat geostationary satellite at pre-set three-hourly intervals and is received at IH Wallingford and three collaborating organisations in Brazil. With a DCP the time slot is set and communication is one-way, from field to base. Within the UK, as an alternative, the extensive Cellular Radio Network has been used by interfacing a logger, via a battery powered modem, to a cellular telephone and pager. At a base a PC, modem and telephone under PC software control transfers data from the field station either automatically or on command with two-way communication which, if needed, can modify the programme of the field logger, for example to change a calibration parameter or alter the time interval between recordings.

SOIL WATER MEASUREMENT

Since the 1960s the neutron probe has been widely used for the routine measurement of soil water content. More recently increasing public concern about possible radiation hazards, its poor accuracy close to the ground surface and unsuitability for automatic logging have encouraged the development of new instruments. Dielectric constant has long been an attractive soil property for determination of water content and its measurement forms the basis of both the TDR (Time Domain Reflectometry) system (e.g. Topp & Davis, 1985) and the Institute of Hydrology capacitance probe (Dean *et al.* 1987). Capacitance sensors, of course, rest on the same basic principles of soil dielectric constant as TDR sensors and in many respects the techniques are complementary. The capacitance probe has been developed for use within an access tube installed vertically in the soil and is available commercially. It has better depth resolution and faster read out than the neutron probe but requires more care in access tube installation.

For measuring the water content in the surface 5 or 10 cm of the soil a significant new development is a portable version of the capacitance probe - the Surface Capacitance Insertion Probe (SCIP). This device is lightweight, relatively low cost and gives instantaneous readings. It is simply inserted into the soil to make a measurement. A description of the SCIP and its application at a field site is given by Robinson and Dean (1993) and its calibration (frequency vs water content) at one site is shown in Figure 1. It has applications for situations including the spatial mapping of surface wetness for flood studies, as well as 'ground truth' for calibrating remote sensing images.

A version of the SCIP has been developed for permanent installation in the soil profile and a logger was modified to operate automatically and form the heart of a field station to monitor soil water content on a continuous basis. Just as Automatic Weather Stations have been in operation for many years, the concept is now extending to Automatic Soil Water Stations (AWSS). Their design has evolved through a number of different configurations, built and tested for specific requirements within the IH research programme. One of the most comprehensive has a rain gauge and three spatially separated arrays each of which measures soil water content, tension and soil temperature. Such advanced ASWS open the way to particularly exciting fundamental studies to determine dynamically the water release characteristic as it is generated in the field by natural climatic events.

DIRECT MEASUREMENT OF EVAPORATION

Evaporation measurement has been fundamental to much of the Institute's field programme since its foundation. Initially only estimation techniques were available, reasonably accurate for short vegetation plentifully supplied with water, but otherwise inferior to direct measurement. With the Institute's experience in this field the 'Hydra' (Shuttleworth *et al.*, 1988) was developed (Fig. 2). It has long been recognised that there is a need for a micrometeorological system for the routine measurement of surface energy fluxes (latent and sensible heat). The Hydra is a compact lightweight mast-mounted device capable of continuous remote measurements of the instantaneous fluxes of latent heat, sensible heat and momentum. The instrument consists of a vertical ultrasonic anemometer to measure the vertical motion of air together with an open path Infra-Red sensing hygrometer to measure

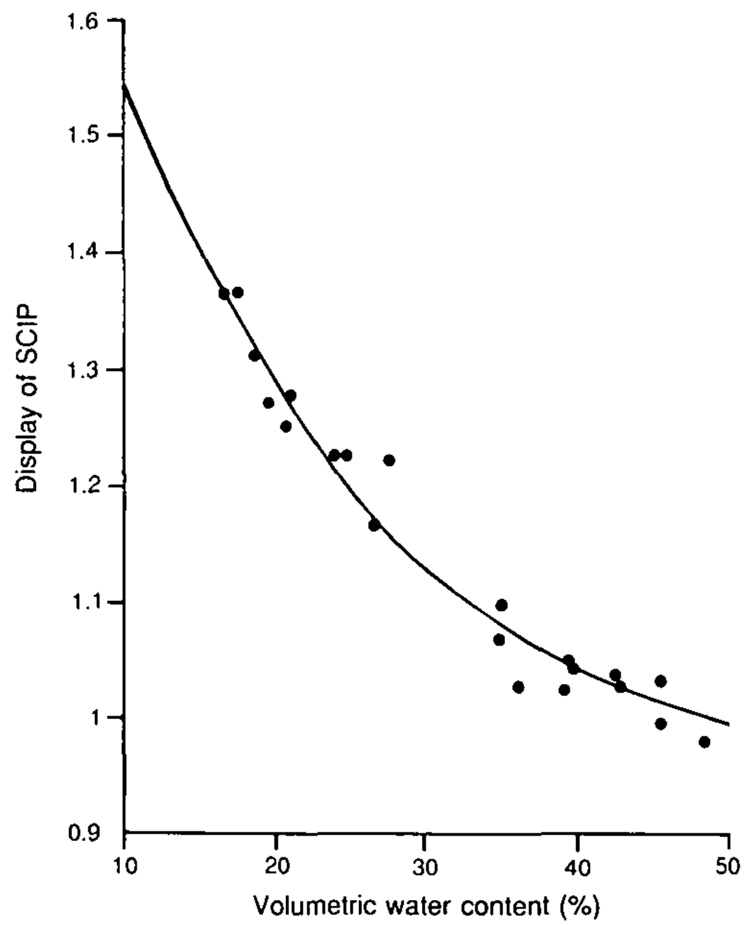

Figure 1 *Calibration of surface capacitance probe readings against water content (using traditional thermogravimetric samples)*

the water vapour concentration in the air, a 3μm thermocouple to measure air temperature and a fast response 6-cup anemometer to measure horizontal windspeed. Each sensor is interrogated at a frequency of 10Hz and the fluxes are computed using the eddy-correlation or eddy covariance principle. The system is controlled by a low-power dedicated microprocessor which as well as interrogating the sensors, computes the instantaneous fluxes using an auto-regressive moving average, and outputs values of the hourly average fluxes, variances and sensor measurements to a removable solid-state memory. The system uses 3.6W of power and will run unattended using two solar-panel regenerated 12V car batteries for up to four weeks before the solid-state memory is full. It can also be linked via satellite for remote monitoring of data. Currently nine Hydra's have been built and used successfully in environments as diverse as Brazilian rain-forest, an Indonesian lake, the Sahel semi-arid zone of west Africa and a glacial frozen lake, as well the UK, France, Spain and the USA. Figure 3 shows the energy balance over one day for a forested site in Brazil.

One recent series of tests was combined with a study of actual evaporation from meadow land with shallow groundwater, just outside Oxford, potentially under threat from nearby gravel extraction. Using the direct measurement of actual evaporation with rainfall and soil moisture measurements, it was possible to obtain an accurate water budget. This showed that actual evaporation was typically only two thirds of the Penman estimate of potential evaporation, emphasising that even with a shallow water table estimation techniques are often in error.

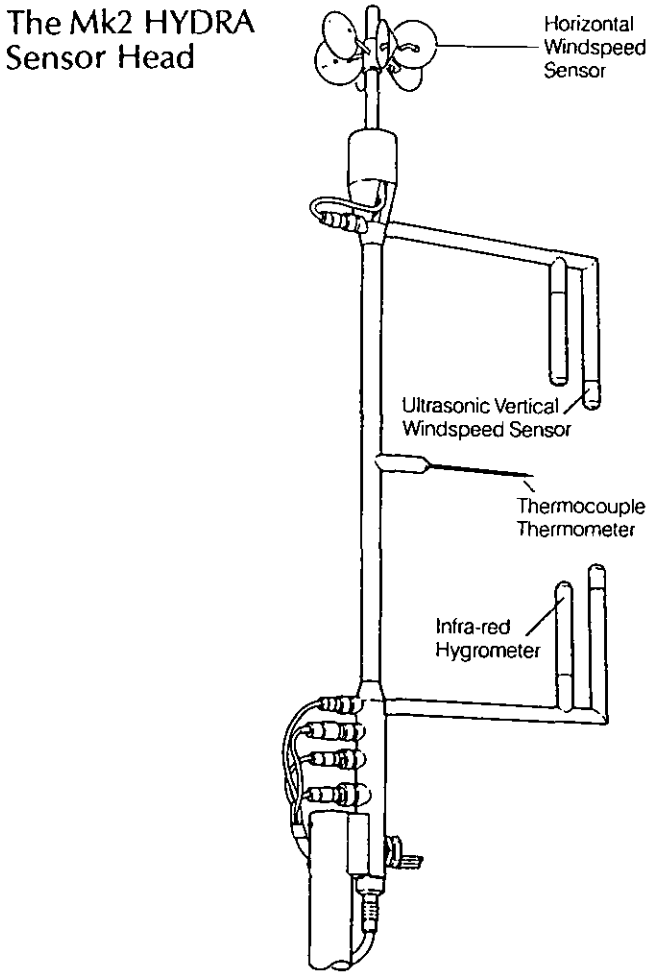

Figure 2 *Components of the Hydra, for direct measurement of evaporation*

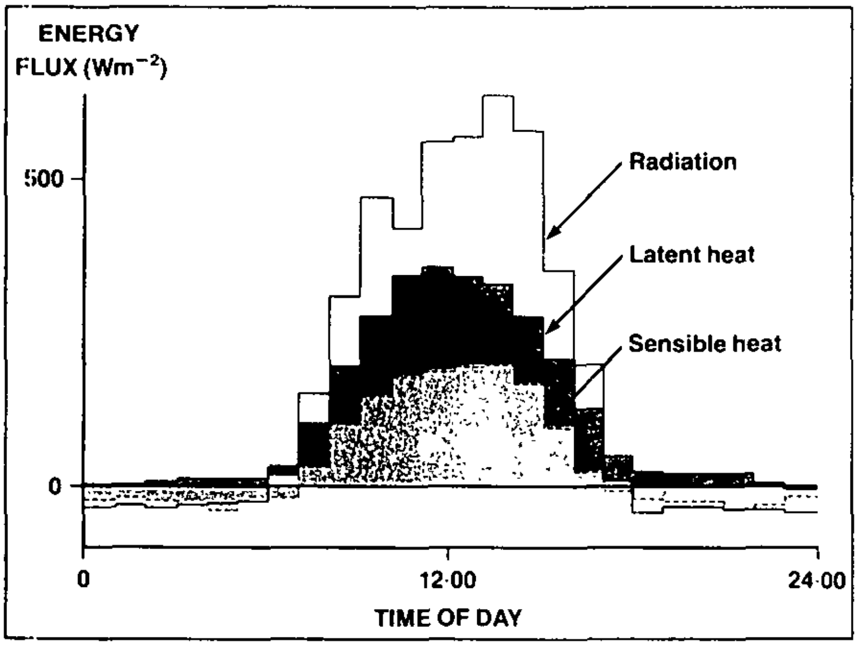

Figure 3 *Typical daily variation in measured net radiation, latent heat and sensible heat for Amazonian rain forest*

RIVER FLOW MEASUREMENT

In the case of flow measurement stations, a variety of data sensing and recording equipment may be deployed to exploit a range of gauging techniques which vary in their suitability according to the precision required and the constraints imposed by the location and physical characteristics of the measuring reach.

The streamflow measurement practices and procedures followed throughout the United Kingdom reflect the characteristics both of the rivers themselves and the catchments they drain. UK rivers - mere streams in a global context - are typically short, shallow and subject to substantial artificial disturbance. With many small basins draining to a convoluted coastline, water resource assessment and management in the UK inevitably involves considerable monitoring effort - the ten largest rivers account for only 30 per cent of the overall runoff. Unsurprisingly therefore, the UK maintains a relatively dense network of flow measurement stations by international standards - approximately one per 150 km^2 (Marsh, 1993). This is a necessary response to the diversity of the UK in terms of its climate, geology, land use and pattern of water utilisation.

Table 1 *Types of primary gauging station in the UK*

Station Type	Number
Velocity-area	430
Flume	100
Broad-crested Weir	30
Compound Broad-crested Weir	35
Broad-crested Weir/Velocity-area	15
Crump Weir	175
Compound Crump Weir	100
Flat Vee Weir	140
Flat Vee Weir/Velocity-area	45
Essex Weir	20
Thin-plate Weir	70
Ultrasonic	50*
Electromagnetic	25*
Miscellaneous	30
Total	1365

* A significantly larger number of ultrasonic and electromagnetic gauging stations have been, or are being, installed and await final calibration and commissioning.

Worldwide, some 90 per cent of all gauging stations are of the open river section, or velocity-area, type. Due to the special hydrometric conditions in the UK, simple velocity-area stations make up well below half of the national network (see Table 1). The small size of most rivers and minimal navigational use together with the attraction of grant-aid from the government (until the mid-1970s), stimulated the design and installation of a versatile group of gauging weirs. These found wide application from substantial lowland rivers to small upland experimental basins. The Institute of Hydrology, principally for research purposes, installed a number of specially designed flumes to address the problem of turbulent flows encountered in steep mountain streams. Where appropriate, laboratory-based calibrations developed for standard weirs were also adapted to accommodate the challenging hydrometric conditions which can be encountered (Hudson *et al.*, 1990). A recent innovation has been the use of aluminium both for new flow structures and for the re-configuration or repair of existing concrete installations. Following a site survey, pre-fabricated aluminium units are assembled prior to their installation on site. The technique is modular and provides a cost effective solution which can be tailored to a range of requirements, for example the reflooring of weirs and flumes.

The ultrasonic method

By the early 1970s, despite considerable hydrometric innovation, arrangements for flow measurement remained unsatisfactory in a number of situations. Particular problems existed on rivers, or reaches, where no stable stage-discharge relation may be expected. Such circumstances occur, for example, where confluences with other streams, tidal influences, sluice gates or other features such as weedgrowth, limit the range of effectiveness of the station control. The effect of these disturbances tends to be especially severe on rivers with a very shallow bed gradient. Difficulties such as these served to stimulate research interest in new flow measurement techniques. Methods based on ultrasound appeared to offer considerable promise. By timing acoustic pulses traversing a river section along an oblique path, in both directions, a measure of the mean flow velocity at that depth can be obtained from the differences in the timings of the pluses. The flow rate may then be computed from a knowledge of the cross-sectional area corresponding to a given depth (Figure 4). Much important development work was completed in Britain and a prototype single-path ultrasonic station was installed on the Thames at Sutton Courtenay in 1973. Further research, building on field experience, led to the introduction of more sophisticated, and reliable, multi-path systems (measuring velocities at different depths) backed up by considerable on-site computing capabilities (Herschy, 1985). A milestone was passed in 1985 when a multi-path system was commissioned at Kingston on Thames to continue the 100-year flow record derived from the complex barrage of weirs and sluices just downstream at Teddington, near London.

The limited range of water levels in controlled rivers like the Thames is well suited to the ultrasonic technique, but by the late 1970s versatile systems were deployed on rivers with substantially greater water level variations. Nowadays 6-15 pairs of transducers are typically used to characterise the full velocity profile. A feature of many modern installations is the attention paid, at the design stage, to ensuring - as far as practicable - a sensibly continuous flow record; access and site facilities are normally excellent with the transducers and instrumentation amply protected against accidental or deliberate damage; some duplication is also common to provide a measure of security against instrument malfunction. Several modern stations provide transducers to enable the measurement of velocities beyond bankfull;

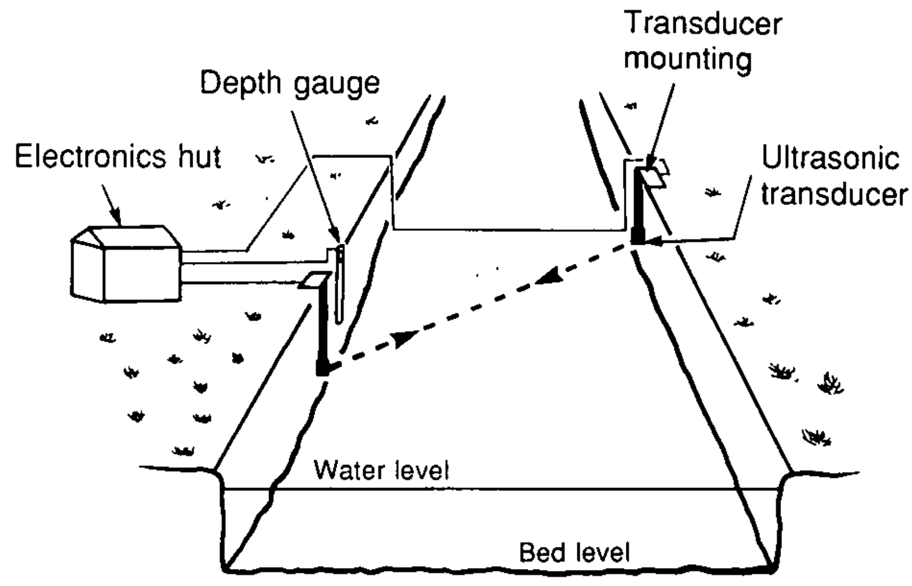

Figure 4 *Layout of an ultrasonic streamflow gauge. (Note: modern installations in the UK typically use more than five pairs of transducers to derive a representative mean velocity)*

the magnitude of floodplain discharge rates is often the least convincingly assessed component in the overall flow.

Remarkably close agreement with flows assessed using current meters has been demonstrated on a number of rivers, including the Thames, and the ultrasonic technique has proved particularly successful in rivers subject to intermittent reverse flow (for instance in tidal reaches). A complicating factor commonly encountered is the presence of an oblique flow pattern (at least under some flow conditions) which necessitates the installation of two sets of transducers on each bank in order to make allowance for the flow direction not being parallel to the channel banks. At a few sites the problem of oblique flow has been addressed by introducing a reflector plate to return the ultrasound beam to a second set of transducers on the same bank. However this option has proved less resilient than the 'cross' configuration which became the most widely used system in the 1980s.

More than 50 ultrasonic stations are currently in operation in the UK rivers, seven are on the Thames alone, and further gauges are to be commissioned to monitor more effectively the major bankside abstractions upstream of London. A few problems can still attend ultrasonic flow measurement, however. Vertical temperature gradients, normally associated with low velocities and high water temperatures, can deflect the ultrasound beams rendering a proportion of the flightpaths redundant. Under such circumstances a full understanding of limited-path operation is essential to maintain accuracy and data continuity. In hot summers, like those of 1989 and 1990 it may become necessary to estimate daily mean flows largely on the basis of velocities recorded through the night. At high flows, high concentrations of suspended solids can also degrade performance by refracting, or attenuating, the ultrasound beam, albeit for a limited period.

The electromagnetic method

For channels affected by heavy weedgrowth or significant bed instability, the ultrasound technique is not a suitable method. Under such circumstances - and where the need for flow data can justify the expense - an electromagnetic (EM) gauging station is often a viable alternative. In recent years the cost of the EM technique relative to flow structures has been reduced and it has also shown the potential to find application in field conditions where, hitherto, more conventional techniques would have been favoured.

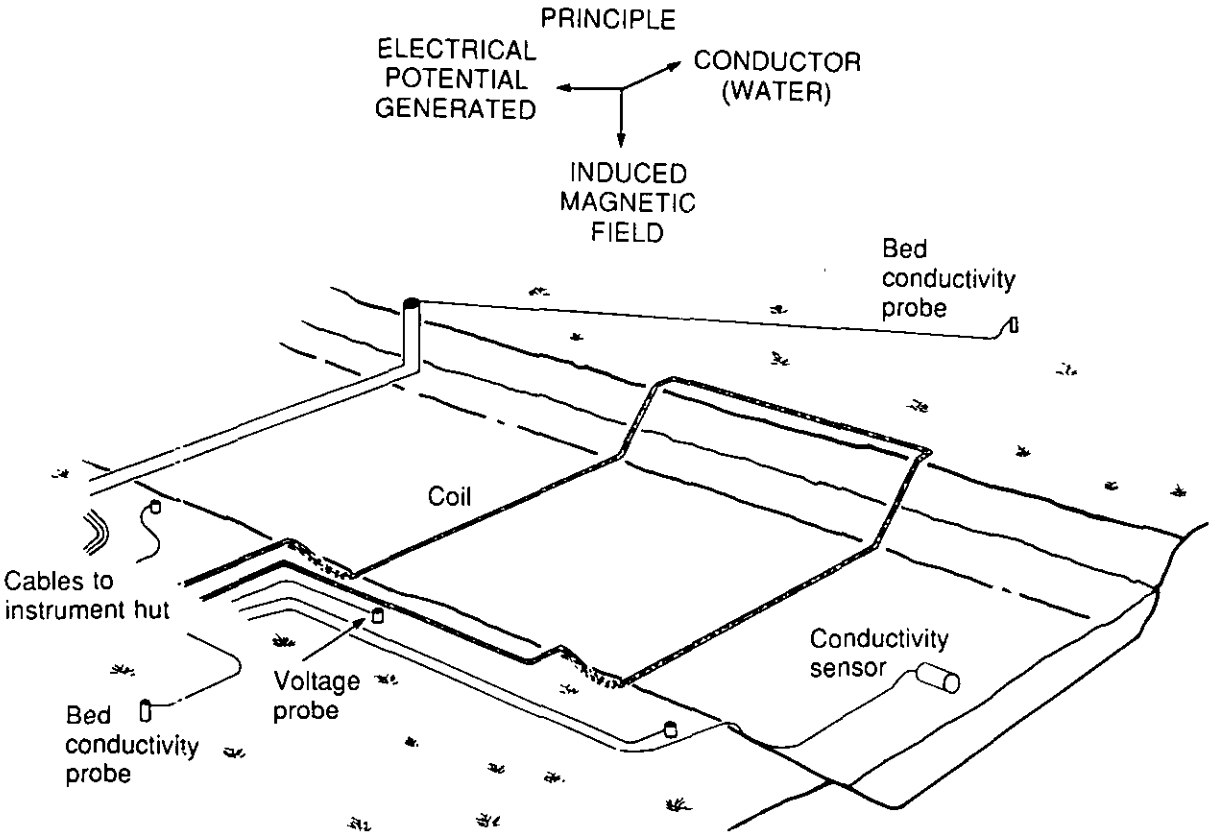

Figure 5 *Layout of a buried coil electromagnetic streamflow gauge. Normally the channel is lined with an insulating membrane*

The electromagnetic technique is only an innovation in relation to river applications. The method was first suggested by Michael Faraday and early estimates of the flow through the Straits of Dover between France and Britain relied on the same basic principle - that an electromotive force (emf) will be induced in flowing water as it cuts a magnetic field (Figure 5). For hydrometric applications a vertical magnetic field is created by a coil buried in the bed of the river or installed above the measuring section; at some sites the coil is installed immediately below a bridge soffit. The coil is normally wound with enough turns of wire to ensure that the field generated is sufficient to induce a measurable voltage between two electrodes (on either side of the channel) at the minimum anticipated water velocity. The development of a viable system in the UK required more than ten years applied research before a practical river flow measurement technique evolved. Particular attention was devoted to the electronics, mostly relating to the need to distinguish the very small induced voltage from a background emf. Improved field performance was achieved by the introduction of an insulating membrane in the measuring section to reduce the affect of 'noise' resulting from the earth's magnetic field. A small experimental installation at Princes Marsh on the river Rother in Sussex provided much valuable design information (Herschy and Newman, 1982) and by 1992, more than twenty electromagnetic stations had been registered on the UK national River Flow Archive maintained by the Institute of Hydrology (Marsh & Lees, 1992).

Early field experience was a little mixed with a few sites operating unsatisfactorily under very low discharge conditions (when only minute voltages are generated). The need for confirmatory current meter gaugings to verify the theoretical calibration also presented difficulties at a few sites - on small urbanised catchments, for instance, where the flashy response allowed little time for a gauging team to be mobilised. Nonetheless, the proven potential of the system together with a continuing - and often severe - weedgrowth problem in lowland rivers led to the deployment of electromagnetic gauging stations in relatively large stream channels, up to 30 metres wide. In such channels the coil is normally buried, for amenity reasons and to avoid inconveniencing river users. This significantly increases the costs and for the larger EM stations the insulating membrane can be unwieldy to handle. Notwithstanding such problems, the value of the EM system was clearly proven in the mid-1980s in, for example, the Southern, Thames and Severn-Trent regions in southern and central England. Several EM stations in the Trent basin now have well over ten years of daily flow data.

The high cost and power consumption have tended to limit the electromagnetic method's application to rivers where other techniques are inappropriate. Nonetheless, the aesthetic advantages of a system which, like the ultrasonic method, can be designed to have very little visual impact may well stimulate its wider use especially where the need for bed insulation becomes unnecessary as ever more discriminating means of signal detection are developed.

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5. Integrated monitoring of mountainous catchments in the Tatras National Park

L. Molnár

ABSTRACT

Integrated monitoring is the basic tool for a deeper knowledge of any environmental system. Monitoring of all natural elements in the Tatras National Park (TANAP) including waters is described. The project called MONTAN is a key part of the Slovakian monitoring programme, planned in stages over the whole country. The paper presents the methodical approach used in the regional monitoring with main attention given to aspects concerning the monitoring of the hydrosphere.

OUTLINE OF THE MONTAN PROJECT

Monitoring of the TANAP region is an integrated project covering a rugged mountainous area of 759 km^2. The Tatras National Park was established in 1949 but it has not been well protected and the environment has been affected by many anthropogenic influences. The TANAP research station was given the task of coordinating monitoring over the area in 1992. Elaboration of the MONTAN project has occupied teams from about forty different institutions for about six months. However, it has proved to be the first well integrated project for monitoring within the area of TANAP. Preparatory work and installation will be organized during the spring and summer period in 1993. The actual start of monitoring is planned for the beginning of the hydrological year in November 1993 or January 1994.

The structure of MONTAN is based on the following natural elements: geological structure, earth surface relief, meteorological and climatological characteristics and air pollution, waters, soils, non-forest vegetation, forest vegetation, aquatic biota, and terrestrial fauna. The nine elements were incorporated into the MONTAN project in the form of interrelated subprojects. Each subproject was individually planned and, according to the complexity of the element studied, subdivided into the required number of themes. The interrelations of the natural elements and/or subprojects are shown in Figure 1.

The natural elements form three basic ecosystems: terrestrial, hydrological, and geomorphological. The structure of the subject natural ecosystems and their interrelations with the selected natural elements are shown in Figure 2. All natural elements are monitored by a number of parameters incorporated into themes. The number of parameters depends on the complexity of the natural system and particularly on its description. The logical vertical interrelations of parameters are the result of the monitored natural processes. The horizontal relations between various parameters of different natural elements are also taken into account. These horizontal interconnections are guaranteed by selected basins and common monitored plots. Coordination of the monitoring intervals is also planned, if possible. Since the scope of this paper does not allow a full description of all the natural elements and their parameters in full detail, attention centres on the hydrosphere.

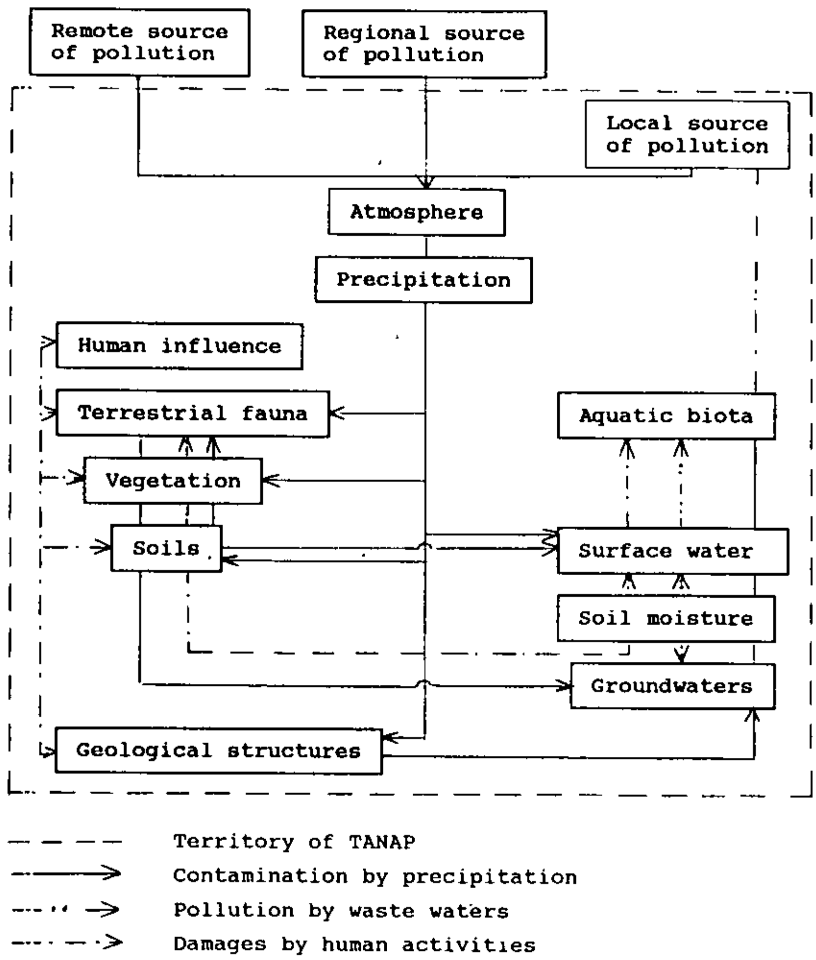

Figure 1 *Schematic representation of the natural elements within the TANAP study area, and the anthropogenic influences*

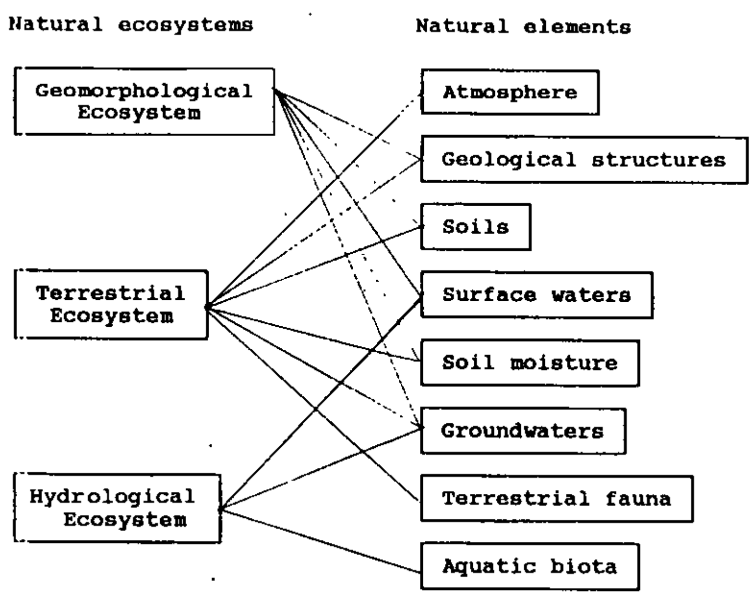

Figure 2 *Linkages between the ecosystems and selected natural elements*

OUTLINE OF THE SUBPROJECT 'WATERS'

Water as the basic medium of the environment is the most decisive element for any form of life in the biosphere and of various processes within the geosphere. Therefore,the knowledge of hydrological processes is a keystone for solutions of many environmental problems. The difficulty of monitoring the hydrosphere increases with the variability of the observed parameters and complexity of the system studied. The natural mountainous environment of TANAP is similar to the other mountainous regions characterized by extremely high variability of all its elements, from complicated geological structure, and rugged topography to unevenly distributed temperature, radiation and precipitation. However, the main goal of monitoring is to describe the interrelations between the natural elements of the environment as a system. The regional monitoring of TANAP hydrosphere has its specific features based on mountainous conditions as well as on the complexity of the subject task and particularity on the description of its parameters.

The main features of monitoring the hydrosphere are:

- complex description of the water and element fluxes through the system,
- continuous vertical observation of the hydrological processes and their interactions,
- spatial determination of processes within the selected catchments and monitored plots,
- temporal harmonization of the observation interval with the spatial scale of monitoring,
- interdisciplinary connection of the hydrosphere with other natural elements of the monitored ecosystem.

Monitoring of the hydrosphere comprises two highly related tasks:

- monitoring of the water balance elements on selected mountainous catchments including monitoring of the hydrological processes on selected monitored plots,
- monitoring the water and element fluxes through the whole studied ecosystem.

The knowledge of hydrological processes allows us to understand the natural water cycle. Environmental conditions, however, are heavily determined by water and transported pollutants.

REVIEW OF MONITORED PARAMETERS AND PROPOSED THEMES

Three basic water balance elements, surface water, soil moisture and groundwater, are monitored by 15 quantitative and qualitative parameters as follows:

a) Liquid and solid precipitation in the catchments
b) Chemical composition of precipitation
c) Interception amounts in forested catchments
d) Water and element fluxes through vegetation and humus
e) Evapotranspiration from selected catchments
f) Transpiration by forest vegetation
g) Surface water amounts
h) Surface water chemistry
i) Soil water amounts in the unsaturated zone
j) Soil water chemistry

j) Spring yield in selected catchments
l) Spring water chemistry
m) Groundwater resources within the catchments
n) Groundwater runoff
o) Groundwater chemistry

Logical interactions between parameters and common technologies of monitoring resulted in these parameters being grouped into the following seven themes:

1. Precipitation and interception in selected catchments.
2. Evapotranspiration from the catchments and transpiration by vegetation.
3. Surface runoff.
4. Fluxes of water and elements through vegetation and humus layer into the soil.
5. Water resources in the unsaturated zone.
6. Spring yields, groundwater resources and runoff.
7. Chemical composition of precipitation, surface water and groundwater.

METHODOLOGY OF MONITORING

Interactions of parameters and natural elements require a well coordinated approach. Therefore, within the framework of nine subprojects, six typical catchments were selected. For the selection the significance of every natural element was considered: geology, relief, location, state of vegetation, biota etc.

In each catchment three monitored plots are proposed. The location of plots is mainly based on their altitude and vegetation cover. They should serve as focal points for the research activities within the catchments. Two of the plots are located on lower and forested sites, the third is located in the subalpine zone. Protection of the monitored plots against conflicting activities is presumed. Standardised instrumentation is planned wherever possible. Time intervals of observations are coordinated taking into account the requirements of different subprojects of MONTAN.

TECHNOLOGY OF DATA COLLECTION

Precipitation and interception data are collected by standard raingauges installed both on open sites and under the forest canopy. Automatic loggers for data recording are used. At remote subalpine sites, standard storage totalizers are used. Snow cover depth and water equivalent are regularly measured. Chemical composition of precipitation samples is also analysed. Daily rainfall recording is replaced by monthly intervals for measurements of totalizers and snow pack.

Evapotranspiration and transpiration determinations require meteorological data: global and reflected radiation, air moisture and temperature, wind speed. Direct measurements of evaporation allow us to determine the gradient of the studied parameter with the altitude. All the data needed for the calculation of potential evapotranspiration are collected by standard equipment at the two lower situated plots within each catchment. For the calculation of actual evapotranspiration data are needed about the soil moisture and vegetation canopy. The important role of the transpiration by forest vegetation requires direct measurement of the water flow through the active xylem of representative trees. The heat balance method proposed by Cermák *et al.* (1976) will be used on selected coniferous trees. Supporting airborn infrared data on surface temperature of vegetation are also planned.

Surface waters are measured at hydrometric stations in each of the six selected catchments. For measurements of discharge the standard water level recorders are used. The catchments vary from 10 to 64 km^2.

Water and element fluxes through vegetation and humus layer require sampling of bulk precipitation, canopy throughfall, and water percolated through the humus layer into the lyzimeters. Chemical analyses of these waters comprises SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, acidity and pH. Water samples will be taken on selected monitored plots. Analyses of the surface layer of humus are the subject of collaboration with the subproject 'Soils'. The time interval of sampling is monthly during the vegetation growing season.

Unsaturated zone water resources are the most decisive parameter for runoff formation in the basin. Their importance is also justified by vegetation demand and terrestrial fauna requirements of water. Continuous measurements are planned at the monitored plots by standard capacitance probes up to 60 cm depths. The data will be recorded on the loggers; the time interval depends on water balance computations. Exchanges of data on the soil hydrophysical characteristics is expected with the subproject 'Soils'.

Spring yields and groundwater runoff are two parameters with different methods of data collection and processing. Measurements of spring yields are planned by standard volumetric method during the two extremes in spring and autumn seasons. Measurements of groundwater runoff in alluvial deposits along the surface water streams will be done by geophysical methods. The spatial distribution of the electrical and thermic fields allow us to identify the groundwater inflow (outflow) to (from) the tributary stream. The interval of measurements is similar to observations of springs. The same method is planned for the determination of bypass flows around the hydrometric stations. Drilling of wells in mountainous areas is not planned.

Precipitation, surface water and groundwater chemistry studies will collect basic information on chemical, microbiological and bacteriological pollution of waters. The complex analyses of water samples include: temperature, pH, conductivity, purity, alcalinity - acidity, organic matter, content of TOC, cations: Na^+, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Fe^{3+}, Mn^{2+}, Al^{3+}, anions: Cl^-, SO_4^{2-}, NO_2, NO^3, PO_4^{3-}, HCO_3, and selected metals: Cu, Pb, Zn, As, Cr, Cd. Analyses also include: content of nonpolar matters and tenzides, and screening of organic micropollutants. The sampling of waters will be organized within the selected catchments in collaboration with teams responsible for monitoring of precipitation, surface water, soil water and groundwater. Time intervals of the water quality sampling are chosen according to typical hydrological and climatical regimes 6 or 7 times a year. The analyses will be done in a single but well-equipped laboratory.

CONCLUSIONS

The scope of MONTAN project requires adequate funding and sound coordination on a domestic level. However, it would be a waste of effort for such a project not to be also incorporated into the existing international network of research basins ERB and well established IHP UNESCO projects FRIENDS (H 5.5) and Hydrology of mountainous areas (H 5.6). Contributions of the MONTAN project to the IHP UNESCO programme should be planned and properly coordinated.

The integrated monitoring of the environment is a costly procedure for the coordinated collection of environmental data in both space and time, for their processing and archiving and their interpretion for the benefit of Society. The final goal of monitoring described here is to identify the anthropogenic influences on the natural environment, its proper management and protection. Therefore, data collected within the MONTAN project will be adequately utilized only if they become part of a well designed research programme.

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6. Mountainous basins - the necessity of intercomparison of hydrological processes inside the basin

P. Miklanek, Z. Kostka & L. Holko

INTRODUCTION

Present hydrological knowledge does not adequately cover the processes taking place in mountainous catchments. Complex topography and harsh climatic conditions make the study of water related problems difficult. The different environmental conditions in individual parts of the basins are expected to result in spatially varying hydrological processes.

The definition of a *mountainous* basin is not precise although the vertical variability of topography is crucial. The small torrents flowing out from the mountains enter wide valleys of the main streams, which can have a character of an extended plain intermountainous depression. The hydrological character of these two main parts is expected to be different.

The main problem is obtaining reliable data. Current meteorological networks in mountains usually do not provide enough data for detailed hydrological studies. Observations are concentrated in lower and inhabited areas, where our knowledge of hydrological processes is also better and more comparable within larger regions.

The great part of the territory of Slovakia is formed by mountains, where the density of observations is inadequate compared to the high variability of the environment. This fact stresses the importance of the study of hydrological behaviour of different parts of the basins.

METHODOLOGY OF INTERCOMPARISON

The study of the hydrological processes should include the following scheme:

- the direct measurement and comparison of data obtained in different parts of the basins;
- the analysis of spatially variable factors (including elevation, aspect and inclination of slopes, vegetation, geology and the soils);
- the analysis of the processes of these individual factors;
- their simple quantification (including variation with elevations, ratios of energy income on slopes, transpiration ability of different vegetation, etc.);
- the synthesis (study of a process and combined factors and/or of hydrological cycle over the area);
- its quantification in the form of areal characteristics (of precipitation,

evapotranspiration, water balance, etc.);

- the elaboration and/or use of modern technologies using up-to-date software and hardware capabilities (digital elevation models, GIS).

The fulfilment of these aims depends greatly on our ability to obtain corresponding data in sufficient time and space density and high quality. The demands put on measuring devices, their number and harsh climatic conditions limit the setting up of a regular network in continuous operation.

Experimental field measurements are of importance as well. They must be organized in a way to enable the analysis and quantification of the processes according to selected differentiating criteria (precipitation measurements in different elevations and orientations to prevailing winds, etc.).

The change of some of the processes can be described by basic physical laws (astronomical, optical, etc.) which makes it possible to model them easily. The use of digital elevation models (DEM) is very valuable from this point of view.

The theoretical predictions need to be authenticated in real natural conditions in selected modelling areas. Such a study was carried on at the experimental basin of Jalovecky creek in the Western Tatras in Slovakia.

CHARACTERISTICS OF THE BASIN AND THE NETWORK

The area of the basin is 46 km^2, and comprises of two distinctly different parts - mountain and foreland, both having approximately the same planar area (Figure 1). The former is typical for its great topographical variability (elevation range 800-2178 m a.s.l.) and is formed by crystalline rocks and a stripe of carbonatic rocks along the contact with Mesosoic complexes on the western divide. The latter is characterized by gently moderated surface (elevation range 570-800 m a.s.l.) and is made of mainly clayey rocks of Paleogene and (rarely) Neogene periods covered with Quarternary sediments. The average altitude of the catchment is 1160 m a.s.l. The vegetation in the mountainous part is represented by spruce forests (44%), dwarf pine (32%) and alpine grass (24%). The foreland is used for agriculture.

The basic network provides data about precipitation, runoff and air temperatures. Snow depths and water contents, evapotranspiration, transpiration and soil moisture contents are measured seasonally. During the period of April 1988 - October 1990 groundwater levels in the foreland alluvium were measured. Soil water content measurements were carried out at eight sites at weekly intervals during May - September 1991. Most measurements are carried out in the mountainous part; the main scientific interests are oriented to the mountainous area as well.

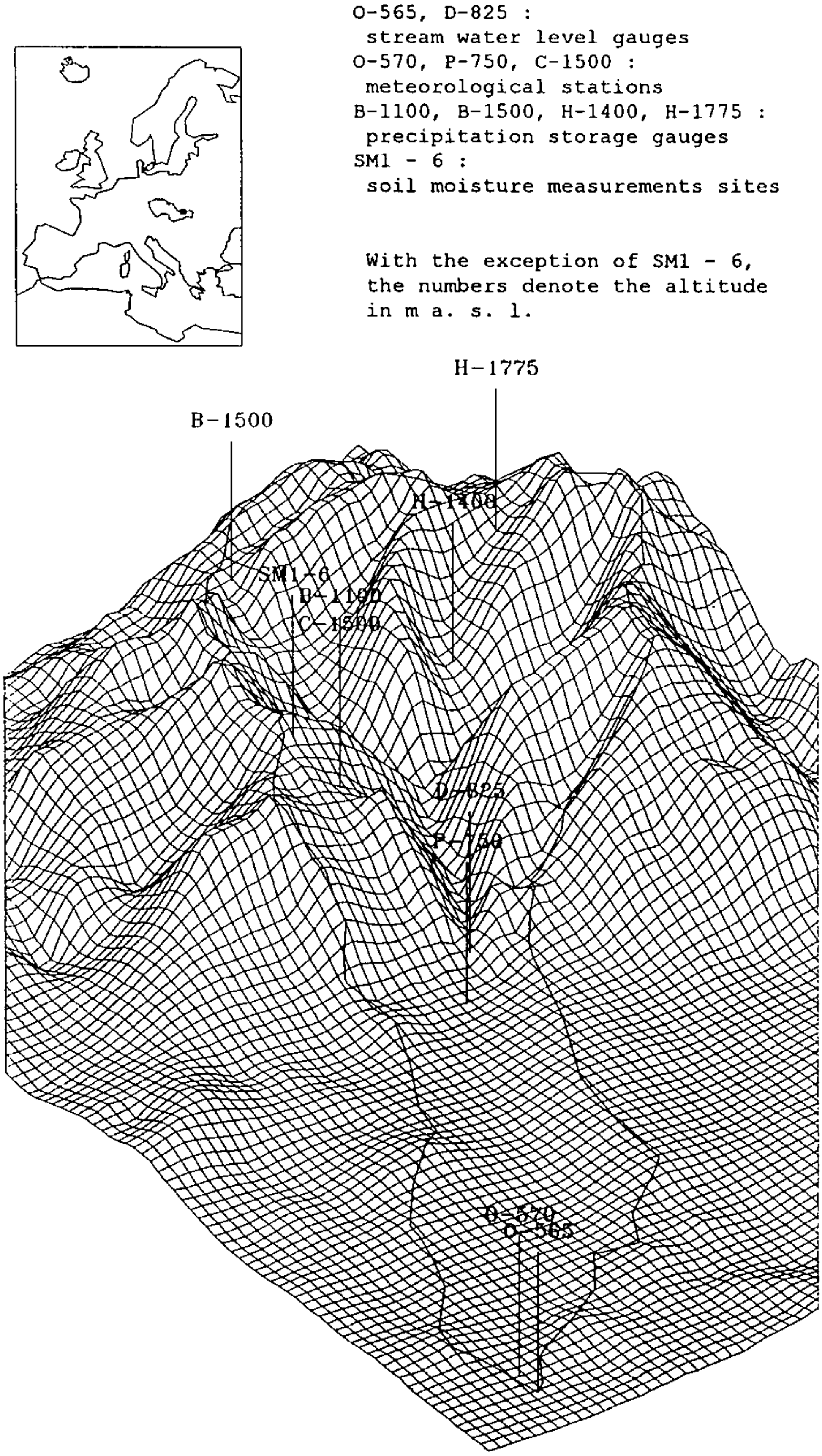

Figure 1 *The Jalovecky potok basin*

ELEMENTS OF THE WATER BALANCE

Precipitation

As the standard network of the meteorological service does not provide enough data, a new network has been built up that consists of seven storage gauges (orifice 200 sq. cm, height 3 m, with Nipher shield) and four standard Czechoslovak rain gauges METRA (orifice 500 sq. cm, height 1 m, unshielded). The measurements are supplemented by pluviographs or tipping-bucket gauges during the summer period.

The comparison of measurements by different types of rain gauges shows no substantial differences in the foreland, while the average annual differences in the mountainous part can reach up to 30% on wind exposed places.

The precipitation variability in mountains is usually expressed by means of precipitation - altitude relationships. An average annual precipitation gradient of 86 mm per 100 m of the elevation was calculated for the period 1989-1991. Linear regression analysis also confirmed seasonal changes in the gradient.

Local precipitation within the basin is determined by many factors, of which topography is one of the most important. Figure 2 shows the mean monthly precipitation in different parts of the basin, for the period 1989-91. Despite the short distance between the sites of P-750 and C-1500, the latter receives much more precipitation.

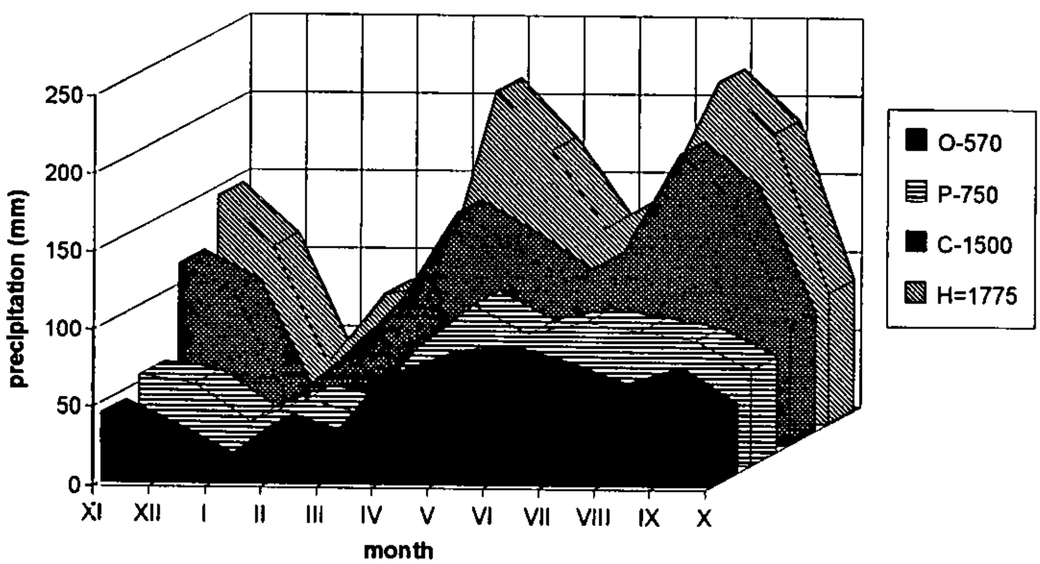

Figure 2 *Mean monthly precipitation (1989-91) at different elevations in the Jalovecky catchment*

The results show the substantial difference between the mountainous and foreland parts of the basin. However, with respect to monthly precipitation each part is relatively homogeneous, i.e. measured local precipitation amounts at different sites within each of the two parts are in good correlation.

However, the shorter the time interval, the higher the local variability. In particular the area adjacent to the mountains - foreland boundary - is subjected to varying influence of mountainous or foreland conditions.

The precipitation regime is one of the important factors affecting the water balance of the basin. Long-term precipitation data revealed that annual regime of precipitation in Slovakia generally follows two patterns, having either one or two local peaks during the year.

The Jalovecky potok basin is situated in the northern part of Slovakia that is generally typical for one-peak annual course of precipitation with the exception of a few stations mainly located on the ridges (Miklanek, 1992). Figure 2 demonstrates the gradual change of the annual pattern with elevation over very short distance.

Nevertheless, the natural variability of precipitation during particular years can result in a regime different from the statistical average.

One of the most difficult hydrological tasks connected with precipitation in the mountainous environment is the estimation of areal precipitation. Table 1 shows the mean areal precipitation in mountainous and foreland parts of the Jalovecky basin calculated as a weighted average based on data from seven gauges.

Table 1 *Basic hydrometeorological data from Jalovecky creek basin, mean values from hydrological years (Nov-Oct) 1989 - 1991*

Month	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	YEAR
PRECIPITATION [mm]													
O - 570	43.9	27.3	8.6	35.4	23.5	64.2	76.7	79.3	69.6	56.2	66.8	44.3	596.0
P - 750	55.1	49.8	26.1	40.2	31.7	73.3	101.8	83.5	91.2	85.8	79.5	60.7	778.7
C - 1500	114.1	96.1	23.5	55.5	91.0	148.2	127.0	104.3	123.4	186.5	156.8	77.6	1304.0
H - 1775	144.7	112.3	36.4	82.1	87.1	212.8	175.0	125.6	146.8	219.8	186.8	84.6	1614.0
Foreland	51.4	42.3	20.3	38.6	29.0	70.3	93.5	82.1	84.0	76.0	75.3	55.2	718.0
Mountain	122.9	99.3	31.0	65.2	90.0	158.6	146.0	116.5	133.0	207.8	170.9	81.2	1422.5
RUNOFF [m^3s^{-1}]													
O - 565	0.656	0.898	0.562	0.566	0.888	1.665	1.932	1.428	0.936	1.248	1.454	1.059	1.108
D - 825	0.398	0.337	0.196	0.174	0.404	1.119	1.500	0.877	0.583	0.799	0.984	0.561	0.661
Difference	0.258	0.561	0.366	0.392	0.484	0.546	0.432	0.551	0.353	0.449	0.470	0.498	0.447
Ratio [%]	60	37	34	31	45	61	78	60	62	60	67	54	60
CALCULATED EVAPORATION [mm]													
O - 570	6.8	0	0	4.1	23.7	43.7	75.6	100.7	117.0	102.3	66.2	36.0	576.2
P - 750	3.6	0	0	0	14.3	34.3	70.3	91.7	113.7	104.9	74.3	36.6	543.7
C - 1500	2.6	0	0	0	13.3	27.8	52.4	81.3	97.7	90.6	56.3	36.6	458.6
Foreland	4.5	0	0	1.4	17.1	37.1	71.9	94.4	114.7	104.1	71.9	36.4	553.4
Mountain	2.3	0	0	0	13.0	25.6	46.3	77.7	92.2	85.7	50.1	36.6	429.4

The expected correlation $(Rn)^2$ between the areal precipitation calculated using seven gauges and the "true areal precipitation" using an infinite number of rain gauges was used as an estimator of the calculation accuracy (Jones, 1989). High value of $(Rn)^2$, e.g. 0.973 agrees with the empirical assumption that monthly precipitation amounts do not differ substantially within the particular parts of the basin.

Daily precipitation totals are necessary for more accurate computations. With regard to the present network it is only possible to transform point weekly measurements of standard rain gauges according to daily measurements in the meteorological station O-570, corrected by pluviograph or tipping bucket measurements. A more dense network would be necessary to compute areal daily precipitation.

RUNOFF

The standard network provides basic data for the whole basin. However, more detailed studies demand additional stations. In spite of this the streamflow is usually the most accurate measured component of the water balance. In Jalovecky creek catchment runoff is measured at the mouth of the mountainous part (D-825) and at the outlet of the whole catchment (O-565). The precipitation regime is reflected in the runoff. Data from the two flow gauges on the Jalovecky creek indicate the greater influence of the mountainous part on the total basin runoff in comparison with the foreland (Figure 3). The contribution of the mountainous part to the total runoff from the basin varies from 30% in February to 77% in May with a mean value of 60% during the year (Figure 4).

On the other hand, the foreland is active in the process of runoff redistribution due to the permeable alluvium. Discharge measurements along the Jalovecky creek have proved permanent recharge of groundwater storage in the highest part of the foreland. Infiltrated water flows parallel to the creek and in the lower part of the foreland enters the creek again.

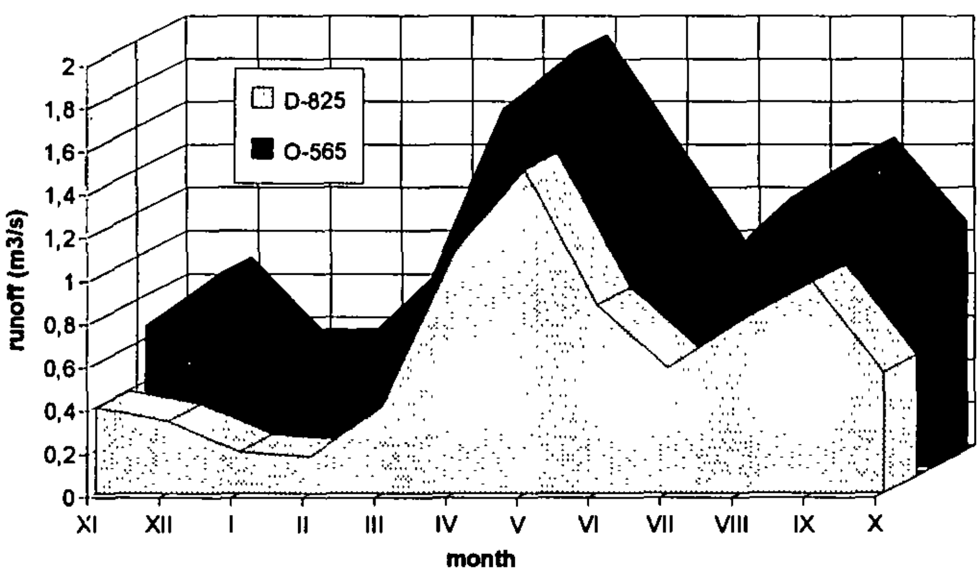

Figure 3 *Mean monthly runoff (1989-91) from the whole basin (0-565) and from just the mountainous part (D-825)*

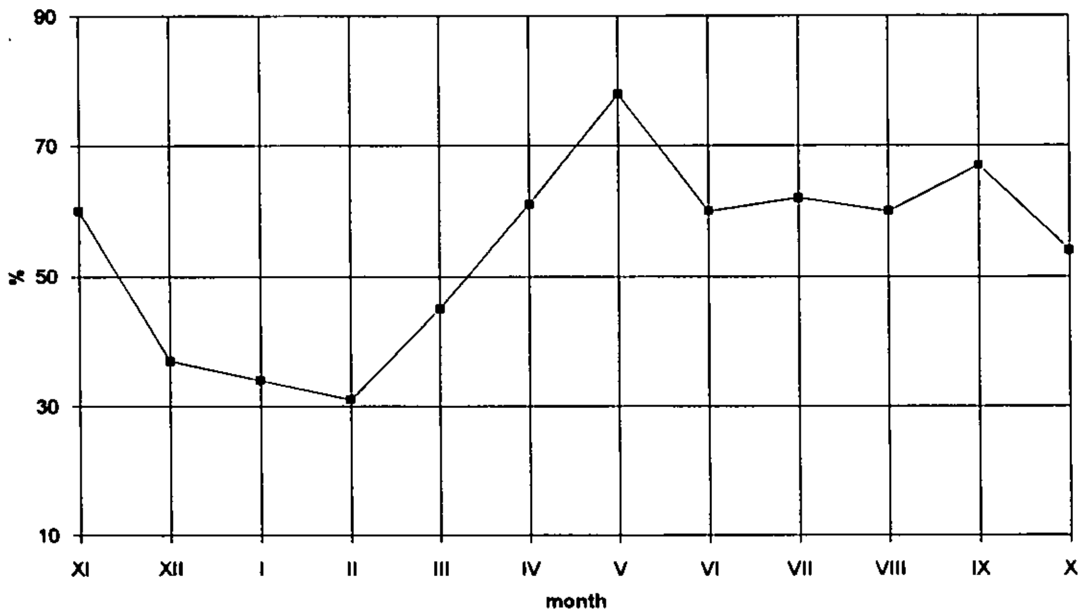

Figure 4 *Contribution of the mountainous part as a percentage of the total monthly flow from the Jalovecky basin (1989-91)*

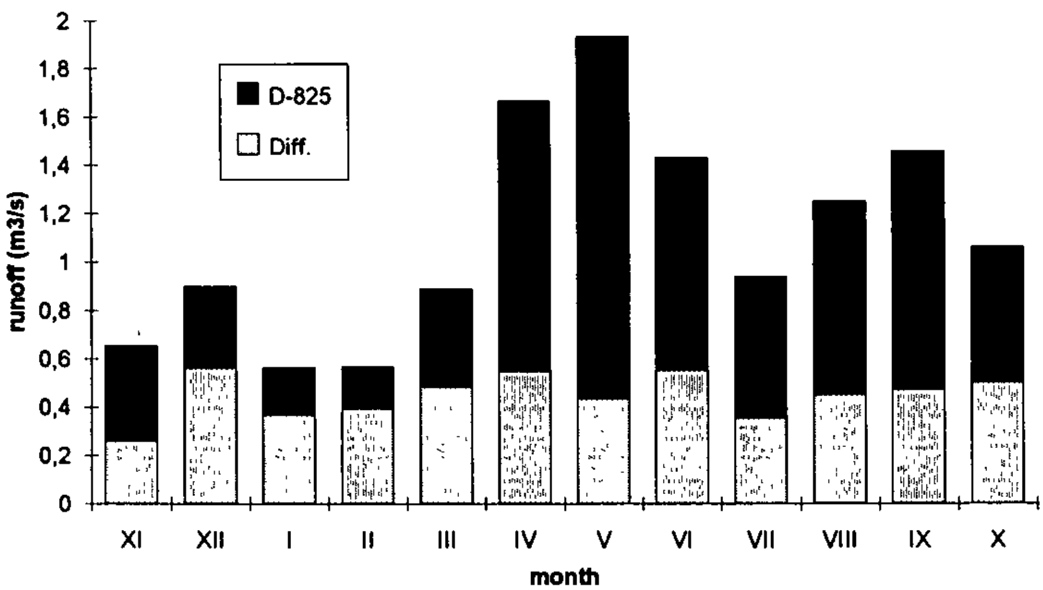

Figure 5 *Monthly flow from the mountainous part (D-825) and the difference between that and total runoff from the whole Jalovecky creek basin (1989-91)*

Due to the earlier snowmelt and the different precipitation regime, runoff from the foreland is more stable than from the mountains (Figure 5). The extreme values occur in November (0.258 m^3s^{-1}) and April (0.546 m^3s^{-1}). The runoff from the mountainous part is more variable and decisive for the regime of the whole creek. Its extremes occur in February (0.174 m^3s^{-1}) and May (1.500 m^3s^{-1}).

The separation of runoff into its direct and indirect components have been carried out based on groundwater - surface water relationships. As the runoff is an areal characteristic the separation provides indirect information about areal infiltration. More detailed separations in the mountainous part of the catchment will be made using stable environmental isotopes.

EVAPORATION AND TRANSPIRATION

Determination of this vital component of the water balance in mountains is connected with difficulties and uncertainties. Some factors in mountainous conditions are favourable for evaporation (soil moisture, wind), whilst others are limiting (net radiation, cloudiness). The limiting factors depend mainly on topography, elevation and slope aspect.

Direct measurements of evaporation are carried on during the vegetation growing season in the main station O-570 and during shorter summer periods in the mountains at C-1500. This vertical range of 900 m enables the determination of the mean gradient of evaporation within the basin. The distance between the stations is about 10 km and there is no orographical obstacle between them. The mean daily gradient of evaporation represents a decrease of 0.1 mm per 100 m in July to 0.035 mm per 100 m in September.

Transpiration was studied in the catchment by Molnar and Meszaros (1990) by means of the heat balance method. Short-term direct measurements of the sap flow through the active xylem of selected representative spruce trees in the mountainous part gave daily volumes transpired by trees of 8-60 l in the forest ecosystem on steep slopes in comparison with 160 l average daily transpiration from a lone standing spruce tree on alluvium during the summer without precipitation.

The measurement of the diurnal courses of transpiration on east and west facing slopes confirmed the influence of solar radiation. An attempt is being made to use transpiration-surface air temperature for extrapolation of transpiration measurements.

The difficulty of direct measurement of evaporation and transpiration forces us to use computational methods. Miklanek (1991) has calculated potential and actual evapotranspiration for different mountainous stations over the period 1956-1980 according to different methods.

More complex methods (Penman, Penman-Monteith, Budyko-Zubenok) require a lot of input data which are usually not available in the mountains. The use of simple empirical methods (Thornthwaite, Linacre, Ivanov) based on one input element is of course limited, but there is good agreement between mean annual values of evaporation calculated by complex and Thornthwaite method (within 1% difference).

Another problem is the determination of areal evaporation from several point values. A simple method was used based on gradients between individual stations and weighted areas of different elevations. As temperature was the only element available as input data for the whole period and different elevations, the Thornthwaite method was used (Jensen, 1973). The results are summarized in Table 1.

Due to the cold climate and high precipitation the moisture conditions in the basin are not limiting for most of the year. The limiting factor for evapotranspiration is expected to be the energy income. Important factors are the astronomical conditions (latitude, season of the year) the atmospheric (air pollution, cloudiness) and topographical (elevation, aspect, inclination).

The astronomical and topographical influences are stable for selected time periods and can be easily described mathematically. It enables us to model the potential energy income for selected points or grid by means of a digital elevation model. Also the atmospherical influence can be incorporated if data on air pollution and cloudiness are available. The expected direct dependence of evaporation and transpiration on energy income will be used for the determination of areal evapotranspiration.

SOIL MOISTURE

Variability of soil moisture regime is the key to the solution of water balance in the soil-plant-atmosphere system. Spatial inhomogeneities of physical properties of the soil profile are the main complication of soil water content estimation. Because of problems with direct soil moisture measurements in mountainous catchment this program was introduced only last year.

Beginning in 1991, weekly measurements of soil water content have been made at eight sites. Volumetric soil samples of 100 cm^3 are taken in steel cylinders and the soil moisture content is determined by the gravimetric method for the soil layers 0 - 10 cm and 10 - 20 cm. Soil bulk density and porosity are also determined. Two sites are on carbonate soil (rendzina) and other six are on podsol soils. All the soils in the Jalovecky potok catchment are sandy-loam or loamy-sand with good permeability. The soil profile is out of groundwater reach.

The sites with northerly aspect show higher soil water contents than the sites with southerly or easterly aspects with the same altitude, soil type and vegetation. The sites with the same characteristics have higher soil water content at higher altitudes (Figure 6). These phenomena are caused by precipitation and temperature gradients as well as by different exposure to radiation. Variability of site aspects and number of sampling sites is not sufficient yet, but it is possible to make some conclusions.

Litovtsenko (1976) presented the correction coefficients considering slope aspect and the soil water content estimations at Caucasus. Comparing our mean values of soil water content at various slope aspects we can obtain slightly different coefficients but in principle having the same interpretation.

Because the soil moisture content measurements are not available from the standard networks, a new method for estimating soil moisture content was introduced. To estimate the soil water content at different points in a mountainous catchment, we adopted an approach based on SMD models (Andersson, 1989; Calder *et al.*, 1983) using the daily sums of precipitation as input values.

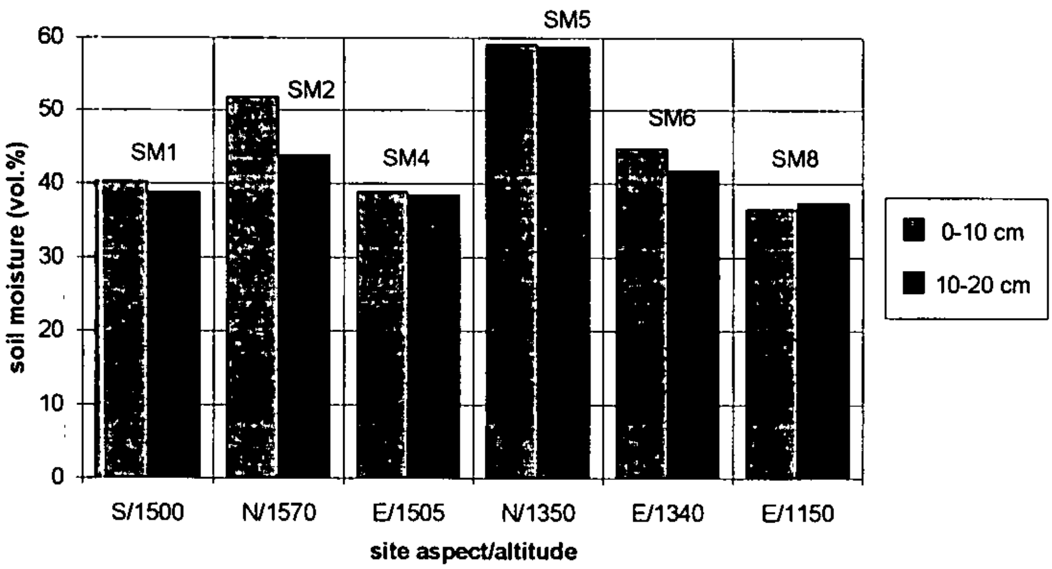

Figure 6 *Mean soil moisture content (May-August 1991) at 0-10 cm and 10-20 cm depths at six sites*

SM1	*1500 m*	*meadow*	*rendzina*
SM2	*1570 m*	*meadow*	*rendzina*
SM4	*1505 m*	*meadow*	*podsol*
SM5	*1350 m*	*spruce, moss*	*podsol*
SM6	*1340 m*	*spruce*	*podsol*
SM8	*1160 m*	*spruce*	*podsol*

The mean daily value of soil water content is calculated from the water content of the previous day increased by daily precipitation and decreased by daily actual evapotranspiration. Daily values of potential evapotranspiration were calculated from the climatological mean after Miklanek (1991) and reduced to actual evapotranspiration using three different transformation functions. They give similar results comparable to measured values.

This method is simple and uses the daily precipitation as input values that are measured in mountain regions. But there are limitations of such a method, including the insufficient input data on vegetation and soil characteristics. This model can give reliable data after the optimization of input parameters. Also, winter conditions are not included in such a simple model.

The main tasks for future research will be the evaluation of the mountain catchment soil variability and the evaluation of a physically-based soil-plant-atmosphere model for various parts of catchment.

CONCLUSIONS

More detailed research is needed to solve problems with respect to time (hydrological year, month, day) and space aspects (point measurements-areal characteristics). The main problems are connected with the extrapolation of daily values of precipitation, evapotranspiration and soil moisture contents over the catchment.

An improvement of the present network, including new methods and longer data series, will be necessary. The remotely uninhabited areas and highly variable environmental conditions would probably never allow the measurements with sufficient density in space and time. It calls for development and more effective use of modern geographical methods of extrapolation over the area. These approaches have to be based on measured data and physical laws (astronomical, optical, gravitational, temperature and precipitation gradients, etc.).

A simple digital elevation model SOLEI has been developed which for individual elementary plots of the basin allows determination of the duration of insolation (sunrise and sunset), aspect and inclination of the slopes and potential income of energy taking into account the surrounding topography. The model is intended to be used for other purposes, such as extrapolation and/or areal characterization of other elements (evapotranspiration, precipitation, etc.). Some GIS based software packages have been used for these purposes (MICROMAPPER) and it is obvious that their wider use is possible and necessary.

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7. Hydrological changes in the Jizera Mountains after deforestation caused by emissions

M. Bičik

ABSTRACT

A comparison was made of streamflow and water quality of a small mountain catchment subject to air pollution. In the ten-year study period the forest was clearcut and replaced by grass. An unexpected finding was only small changes in hydrological regime, with perhaps greater variability in the relation between summer precipitation and streamflow. Water chemistry changes were much greater over this period, although some ions (AL^{3+}, K^+, NO_3^-) did not follow expected trends.

INTRODUCTION

In 1981 the Czech Hydrometeorological Institute (CHMI) started hydrological and hydrochemical observations in headwater catchments of the Jizera Mountains. This is an important region for wood production, drinking water supply and recreation. It was at this time that the first evidence of damage to spruce forest caused by emissions of SO_2 was found. All the region is affected by air pollution. Emissions come from coal burning electric power stations in North Bohemia, Poland and Germany. The amount of ions carried by air into mountains influence the chemistry of water in the basins. The aim of the project was to discover the influence of changes in forest ecosystem upon the hydrological regime of this area and changes in stream water chemistry.

The damage to the forest was faster than expected and for economic reasons the dying forest was clear-cut. Reforestation went on slowly and was not fully successful. In ten years all headwaters of the mountains were completely deforested. Now ten-years hydrological data from the period 1982-1991 are being processed in order to obtain information for the restoration of the mountain ecosystem and for securing the drinking water supply to the cities of Jablonec and Liberec.

GENERAL INFORMATION

The Jizera Mountains are located in the North Bohemia region (latitude 50° 50′, longitude 15° 15′) on elevations of 700-1000 m. The geology comprises a granite massif covered by a thin, non-continual bed of eluvial sand and gravel. In depressions there is sandy clay and in some places are layers of peat. The overlying soils are podsols and peat.

At the start of the study in 1981, 95% of the area was forested (mainly Norway spruce forest except the northward slopes which are covered by beech). By 1991 the areas above the elevation of 800 m that was covered with spruce had been completely deforested and turned to grass areas; however the beech forest is still prospering. In all about 90-95% of the forest area was cut down.

Climatic conditions - mean air temperature at 780 m elevation is +4.4°C, annual precipitation is 1300-1600 mm. Snow cover lasts from December to April.

RESEARCH BASIN INFORMATION

The CHMI manages two small basins: a) "Uhlířská" : the "Černá Nisa" river, 2.9 km^2, 780-890 m, the west part of Jizera Mts, and b) "Jezdecká" : the "Černá Desná" river 4.7 km^2, 790-1050 m, the east part of Jizera Mts.

Measurements started in the autumn of 1981. Both the basins were clear-cut in the period 1986-1989. In 1985 and again in 1988-1990 the area was limed. This paper describes results for the larger of the two basins, the Jezdeckà catchment.

CHANGES IN HYDROLOGICAL REGIME

The annual water balance and summer runoff patterns were studied. Contrary to expectations there was little apparent change when the forest was clear-cut. The general water balance did not change: the double-mass curve from the ten-year period with daily data does not show any deviation (Figure 1). The runoff patterns were also studied using daily data in summer months (1 June - 30 September) divided into two successive five-year periods: the frequency analysis of summer discharges did not shift (Figure 2). Only the rainfall-runoff relationships showed a small evidence of changes (Figure 3). In the more recent period these relationships expressed in a linear model have a greater degree of variability and thus a lower correlation; but the effect is weak.

A number of other studies in heavily polluted areas of the Czech Republic have also found little hydrological change when damaged forests were cut down (e.g. Bubenickovà and Kasparek, 1990; Krecek *et al.* 1992).

CHANGES IN SURFACE WATER CHEMISTRY

In the lower part of atmosphere in the Jizera Mts. the average concentration of SO_2 was 19.3 μgm^{-3}, and in industrial areas it reached values of 35-40 μgm^{-3}. The average concentrations of some metals in airborne particles are abnormally high: Cd (2-3 μgm^3), Pb (60 μgm^3), Fe (500-700 μgm^{-3}) and Ni (100 μgm^{-3}). The average concentrations in wet deposition were important: sulphur anions (7-10 mg/l), NH_4 (0.15-0.19 mg/l), Cd (0.7-2.0 μg/l), Ni (1.0-2.5 μg/l) and high amounts of many other heavy metals. In streamflow a large range of parameters were measured. In the observation period 1982-1991 the concentration of SO_4^{2-} increased from 5 to 15 mg/l (Figure 4) and the pH fell from 5.5 to 4.9 (Figure 5).

The import of sulphur anions started the increase in acidity and secondly the leaching of some elements from substrata. The dependence of components on pH value was studied. Significant correlations with pH were found: Al, Na, Fe, Zn, Mn, SO_4^{2-}, HCO_3. In contrast there was no dependence on pH for the following cations: K, Mg, Ca, Cu, Cr, Ni, Pb, Ag, Cd and the anions Cl, NH_4, NO_3, PO_4.

We expected that the concentration of Al^{3+} and of some heavy metals would increase and the concentration of alkalic metals (Ca^{2+}, Na^+, K^+) would decrease. The study of time trends of the concentrations of elements showed that Ca^{2+} really started to drop (3.5 to 2.0 mg/l in 1982-1985), but that following liming by 1985 it had increased and in 1991 reached the level it had been in 1982 (Figure 6). As expected, a decrease in concentration of Na^+ and the increase in amounts of Mn, Ni, Cd was found, but many ions did not fulfil the expected trends (Mg, Mn, Fe, Zn, Cu, Pb, Cr, Cl^-) and some have quite opposite ones: Al^{3+} had a decreasing (and not an increasing trend), although this was not statistically significant (Figure 7). K^+ had an opposite trend to Na^+ and also NO_3 had an opposite trend to SO_4^{2-}.

In some cases the concentration of Al^{3+}, Cd^{++} and Mn^{++} exceeded the level of Czechoslovak Standard for drinking water.

DISCUSSION

From the above results we can see that the anthropogenic influence of emissions has had more impact on water quality than on quantity.

In non-extreme runoff conditions the new vegetation cover of the catchment (grass) gives a very similar runoff response to the old one (spruce forest). The reason is unclear; whether the evaporation from the damaged forest was already reduced or if grasses replacing the dying trees had similar rates of evaporation. Due to this finding no further necessary measures have been undertaken for safeguarding drinking water quantity. For flood protection, however, the research study will continue further.

The chemistry of the massif of Jizera Mts. has a specific regime. Not very high SO_2 concentrations in the air caused an increase of SO_4^{2-} in the surface water and thus also its acidity. The granite massif does not have the ability to neutralize the atmospheric deposition and is very sensitive to the changes in chemistry balance. The influence of the liming on surface water acidity cannot be detected; it looks as though there is no effect, but possibly the period of observation is still too short. Since 1988, atmospheric pollution has begun to decline due to the closure of some of the coal burning power stations, so SO_4^{2-} in surface waters may decline in the future (although concentrations are at present still increasing).

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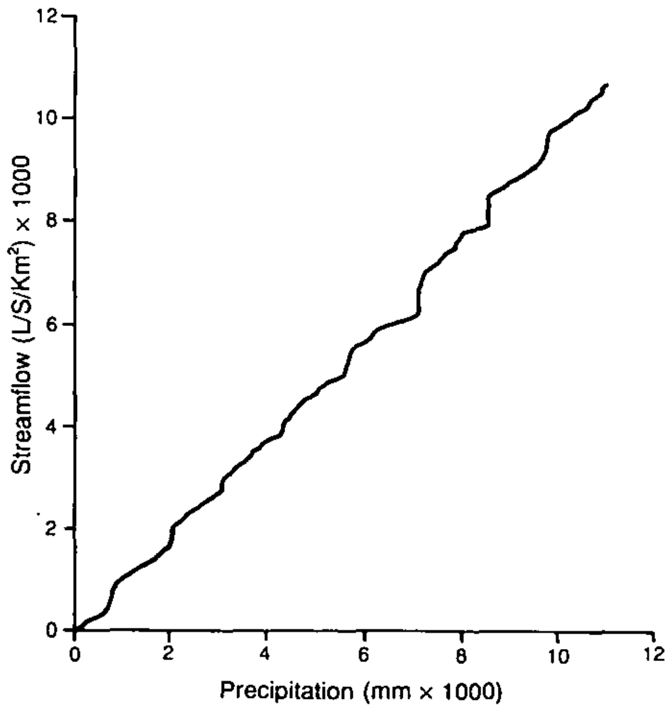

Figure 1 *Double mass curve of precipitation and streamflow (1982-91) for the Jezdecka basin*

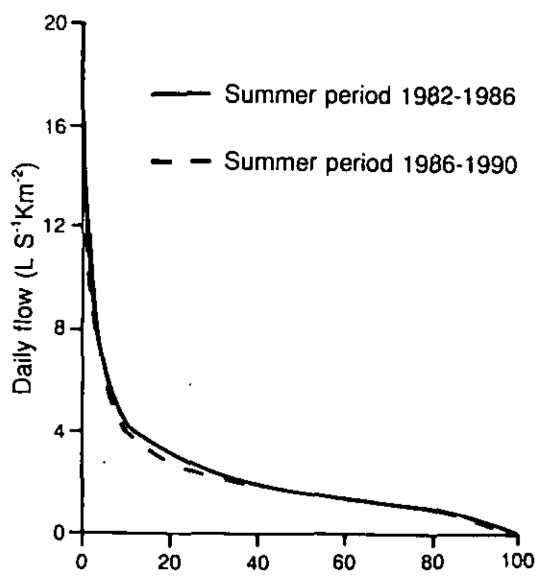

Figure 2 *Comparison of daily flow duration curves for summer periods in 1982-86 and 1986-90*

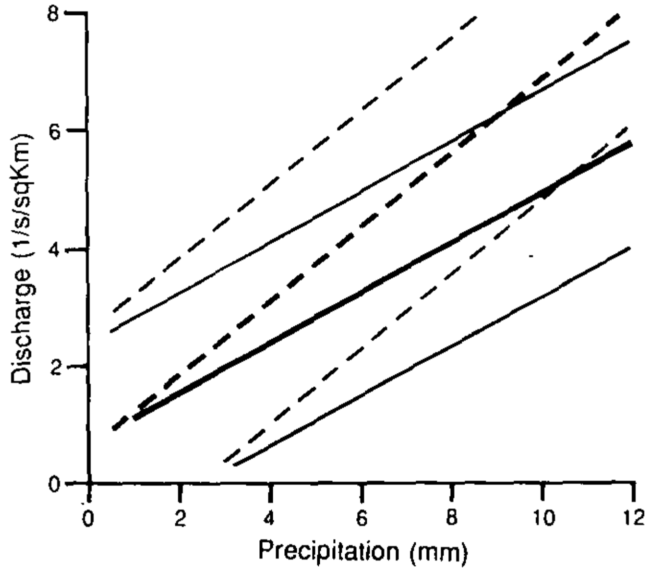

Figure 3 *Linear regression lines and confidence intervals of flows and precipitation (seven-day averages) for summer periods in a) 1982-86 (dashed lines) and b) 1986-90 (solid lines)*

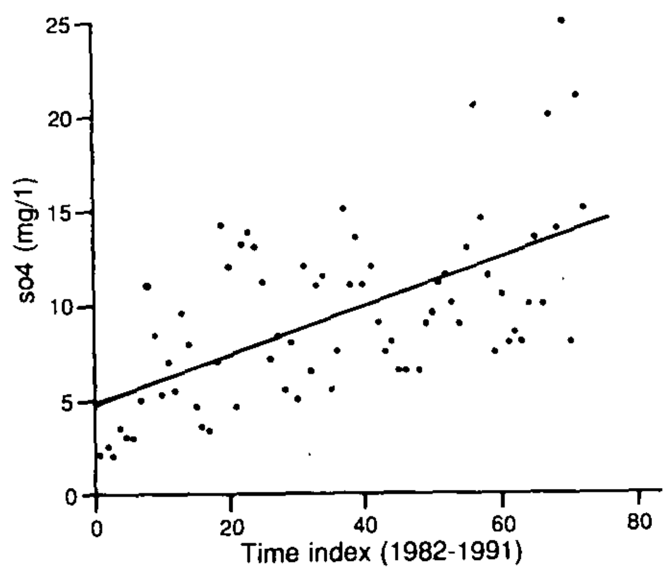

Figure 4 *Streamwater SO_4 concentrations (1982-91)*

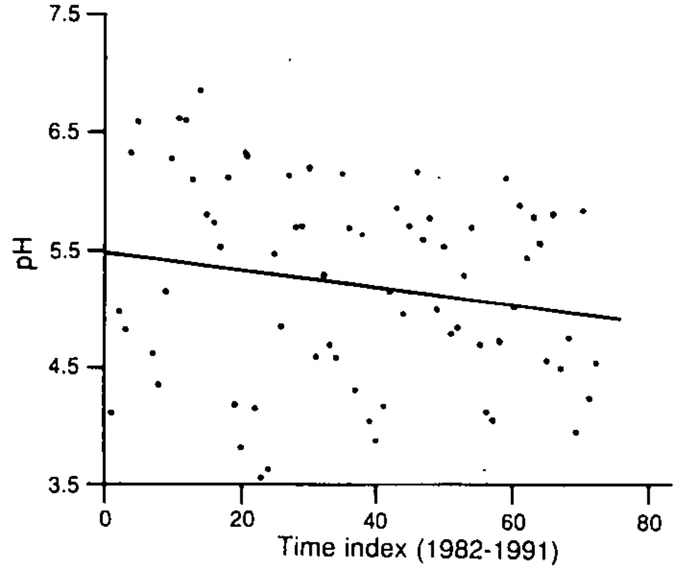

Figure 5 *Streamwater pH (1982-91)*

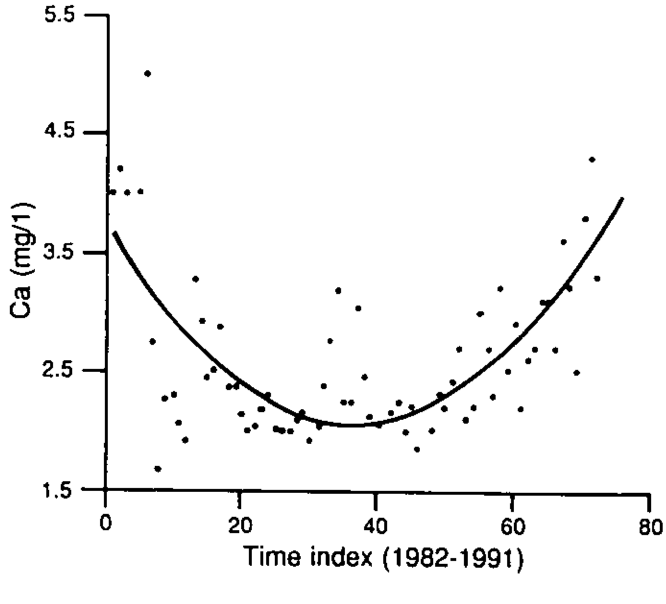

Figure 6 *Streamwater Ca concentrations (1982-91)*

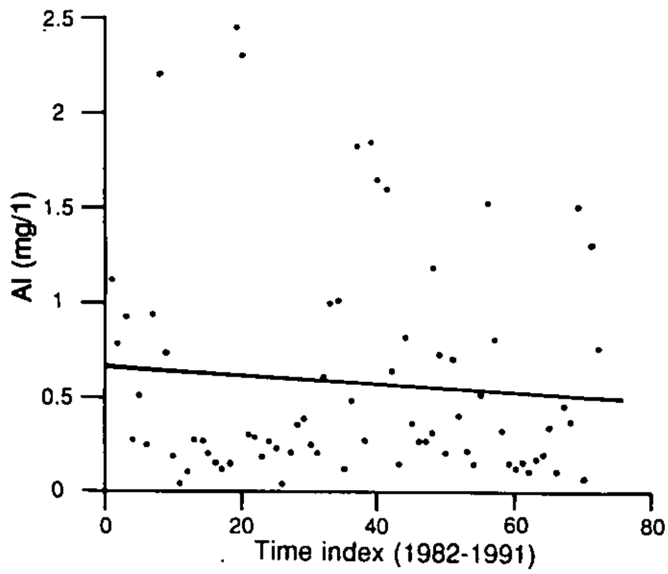

Figure 7 *Streamwater Al concentrations (1982-91)*

8. Tools for budgeting nutrient transfers in agricultural catchments

C. Cann

ABSTRACT

Nitrogen and phosphorus transfers from rural areas to streamflow have been studied since 1975 in the Coet Dan catchment, an experimental representative basin. In order to determine the relative importance of factors affecting nutrient transport, two other catchments with different physical characteristics, land management and husbandry intensity have been studied since 1991. Some results are presented and several kinds of comparison have been made, leading to a discussion about methodology showing the complementarity of these comparisons and the importance of long term data records.

INTRODUCTION

If a catchment is considered as a closed system, the balance between the input and output of any element may be calculated in order to quantify processes and storage within the basin. The scale of the catchment is very convenient since the water and the elements carried by the water pass through the same outlet and thus their respective outputs may be measured. Of course it is absolutely essential that underground water, and any solutes within it, are not carried away unmeasured. In an experimental representative basin, a geological study can be carried out to verify that there is no water loss due to underground permeability or, in the event of such water losses, these can be measured.

It is much more difficult to quantify the anthropogenic input and output or the gaseous losses of an element. In forested or mountainous catchments, the few anthropogenic effects can be controlled, but in urban or agricultural catchments it is not possible to closely monitor all the anthropic inputs and outputs, though it is in these basins that the balance is the most interesting.

Water pollution by nitrate, phosphorus, pesticides etc. is increasing and many research studies have been carried out to understand these water and solute transfers. Comparisons seem to be the easiest way of studying the influence of human activity on water cycle and solute cycles.

Such comparisons can be done on a single basin to compare water and solute transfers before and after a change in human activity. However, we cannot make a comparison between only two years, one before the change and another after the change, because of the natural variability of rainfall and evaporation between years which influence water and solute fluxes. Thus we need many years of data, both before and after a change, to be allowed to make a statistical treatment.

Comparisons can also be made using paired basins, one being influenced by the human activity to be studied and the other one being free of it. The difficulty is to find two basins having the same physical characteristics and used in the same way by other human activities. We never found such twin basins and we always have to estimate the influence of the differences.

COET DAN CATCHMENT

In order to draw up the balance for chemical elements, the CEMAGREF has used various methods of obtaining data in the Coet Dan E.R.B. in central Brittany since 1971. Direct measurements are made with several rain gauges allowing us to record rainfall depths and to analyse rain water chemistry, and a streamflow gauge with automatic samplers is used. Samples are also taken manually at several places to find the sources of nutrients observed at the outlet of the catchment.

The water table and water quality is recorded in five piezometers spread over the basin to survey groundwater movement. A line of five small piezometers is used to measure the subsurface flow on a slope and three groups of deep piezometers, one of them being at the outlet of the basin, give us data on underground flow. The bedrock is a schist and although it is very fissured there is only very little underground flow.

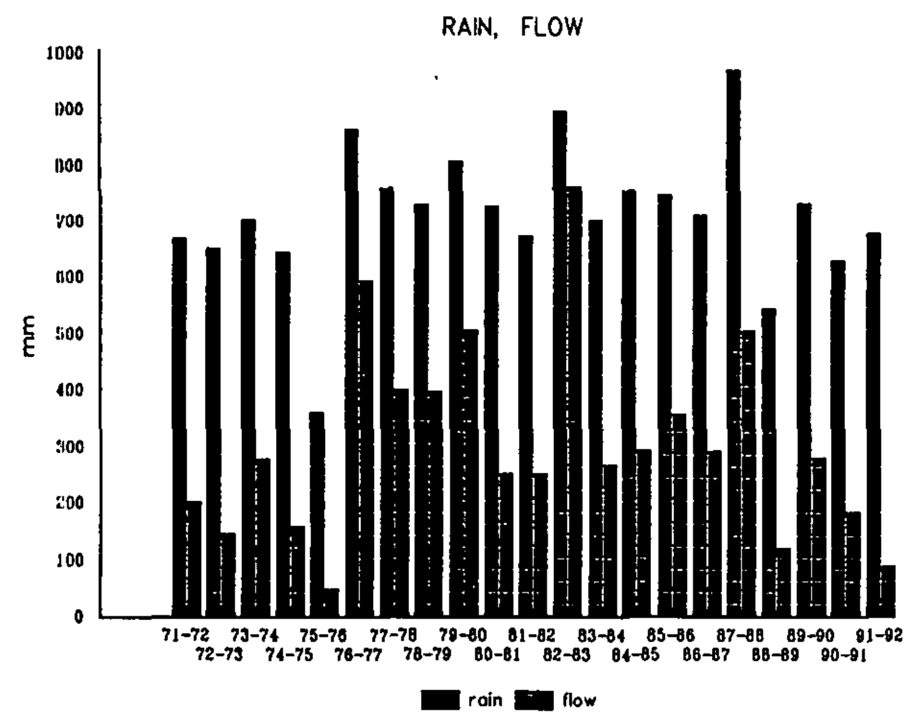

Figure 1 *Annual rainfall and flow for the Coet Dan catchment*

Very intensive agriculture occupies approximately 90% of the 12 km^2 basin. This provides most of nitrogen and phosphorus input and a large part of the output. Two exhaustive surveys were carried out, in 1988 and 1991, to pinpoint all nutrient movements in the form of fertilisers, animal feeds, fodder as well as manure, sewage, crops, animals and animal products.

An analysis of the results provided an evaluation of the fertiliser application per field, per farming unit and for the basin as a whole for nitrogen, phosphorus and potassium. It shows that the quantity of fertilizers applied to fields and farm units does not match requirements; in most cases there is a large excess of fertilizers.

Soil analyses have confirmed phosphorus enrichment due to excessive fertilization. An annual survey since 1984 of crops and farmers' practices for fertilization have shown a strong relationship between phosphorus concentration in soils and excess of appplication of fertiliser. This type of analysis can be done for phosphorus because this element is very strongly adsorbed on soils and river losses constitute a very small part of the storage of the basin's phosphorus: far less that 1°/°°.

For nitrogen, it is more complicated because this element is not adsorbed, it is leached down by water and moves in soil and groundwater. Further, ammonium volatilisation and denitrification produce gaseous losses. These physical and chemical reactions depend on temperature, humidity, soil composition and microbiology, ammonium and nitrate concentrations etc. Thus, it is very difficult to measure these losses, even in a very small catchment or in a field, and much more difficult to measure it in a large basin.

It is, however, possible to quantify gaseous losses from the balance between nitrogen input and output, taking into account the storage variation shown by soil analyses. Input data at different scales is known from the inquiries and the surveys. Output is calculated by measurements at the outlet of the basin.

This was done in the Coet Dan basin in 1988 and 1991. To verify the accuracy of the ratios that we calculated, we are now trying to measure gaseous losses directly but it is very difficult to take and analyse representative air samples and to establish the flow of losses. A very large number of analyses are needed because of spatial and temporal variability. Thus the method of budgeting will always be the simplest way of quantifying these gaseous losses.

COMPARISONS WITH OTHER BASINS

To test if our ratios are representative, we are now calculating the balance for water, phosphorus and nitrogen in several other catchments in Brittany. Two catchments have been chosen in which to install raingauges, streamflow gauges, automatic samplers and piezometers in order to collect data about rainfalls, discharges, concentrations and flows.

The Yar catchment, in north Brittany, is a 60 km^2 basin. Agriculture is also the principal activity but is not as intensive as in the Coet Dan basin. There is some woodland and some badlands (too wet for cultivation) and the major part of land is used as grassland. The bedrock is granite which gives a greater underground flow than in the Coet Dan basin. Data have been collected since 1991.

The Quillivarou catchment, in north west Brittany is 5 km^2 in area. The agriculture is as intensive as in the Coet Dan basin with a large number of poultry and pig production units, wheat, corn and potato fields. Grassland covers no more than a quarter of the land and the majority of them give high yields. The catchment is sited on granite bedrock as is the Yar catchment. Data have been collected since 1992.

Thus, these three experimental representative basins allow us to make four types of comparisons.

1) Comparison between years on the Coet Dan basin, to monitor the influence of intensification on transfers. The development of pig production and increasing nitrate flows shows the importance of that comparison before, during and after intensification.

2) Comparison between catchments on schist and on granite bedrock using the Coet Dan and Quillivarou basins. The relative lack of groundwater storage in the first basin leads to drying up of the stream during most summers and induces high variability of solute concentrations and discharge after rainfall. In contrast on the Quillivarou basin, the stream does not dry up and concentrations and discharge are subject to less rapid change.

3) Comparison between catchments farmed more or less intensively shows the influence of intensification on solute flows and concentrations. This can be done using the Yar basin and the Quillivarou basin. It was also done in the Coet Dan basin in the first comparison.

4) Comparison of the influence of intensification according to the nature of the bedrock. The increase of concentrations with intensification does not work in the same way, whether there is an important underground water storage or not. In the Coet Dan basin, on a schist bedrock, with a very little underground storage, concentrations of solutes rise to very high levels although they remain lower on granite bedrock basins even when the total flow is as great.

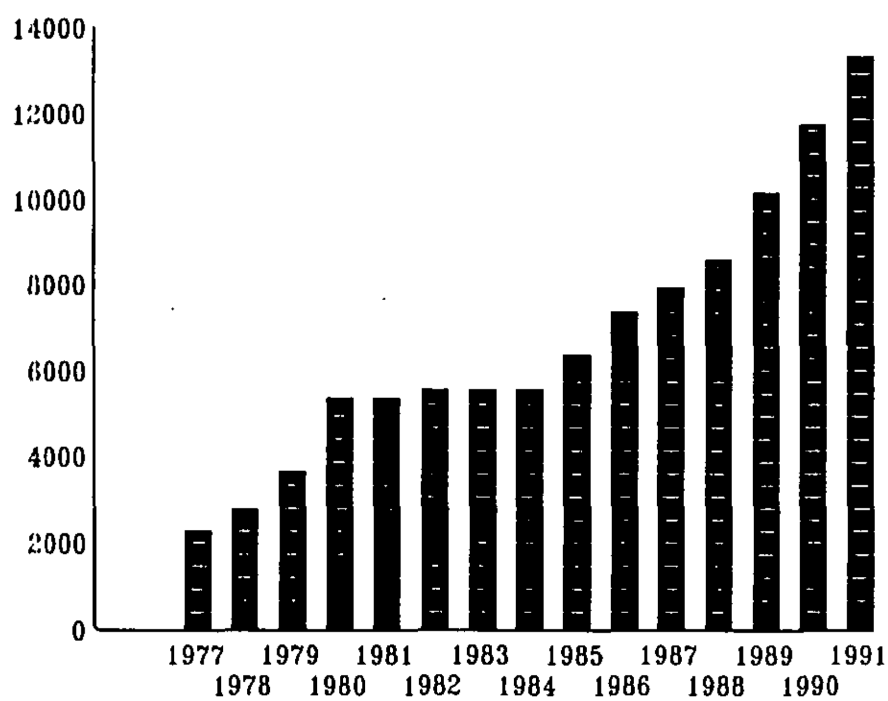

Figure 2 *Number of pigs in the Coet Dan catchment*

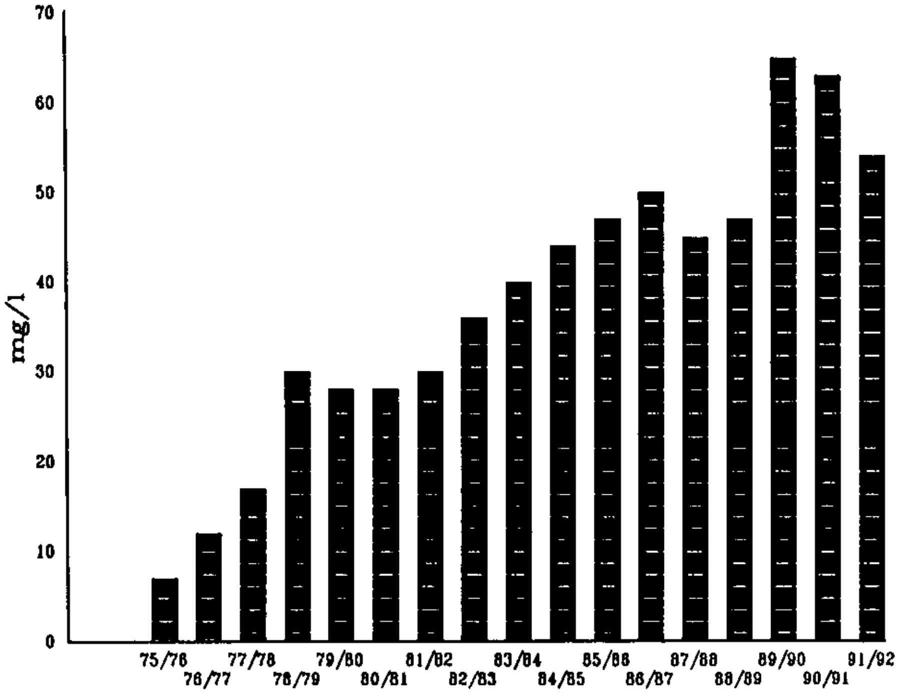

Figure 3 *Streamwater NO_3^- concentrations in the Coet Dan catchment*

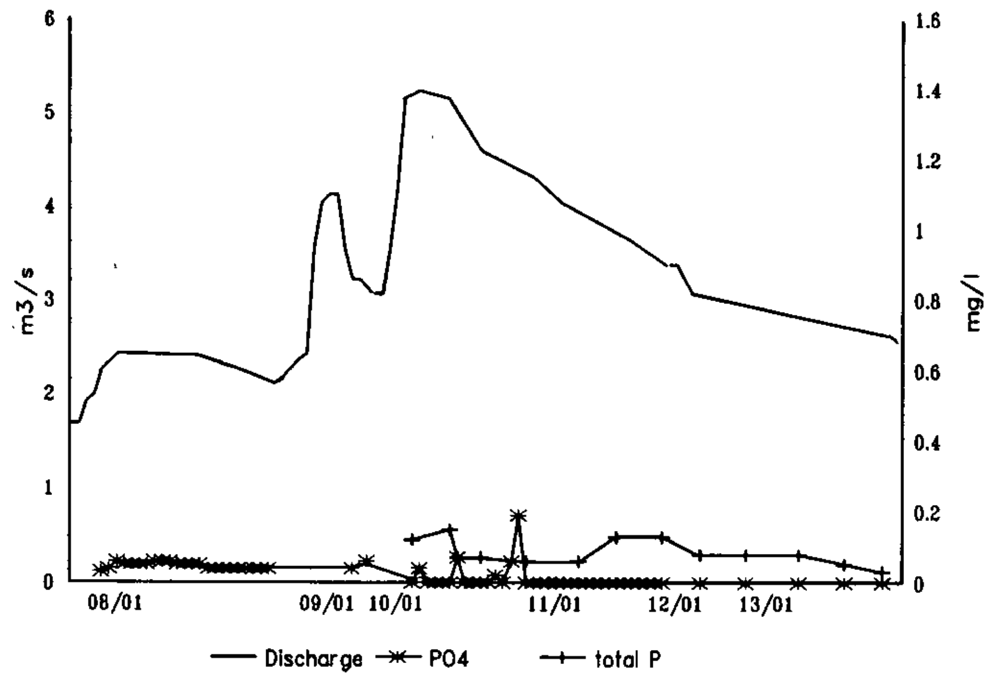

Figure 4 *Stream discharge and PO_4, P concentrations in the Yar basin 8-13 January 1991*

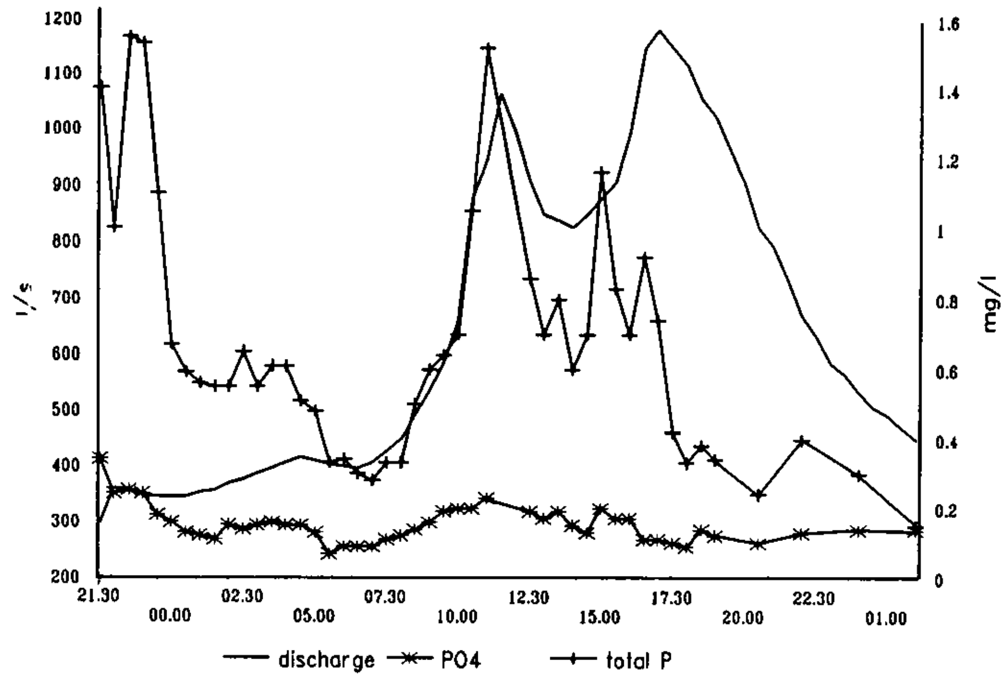

Figure 5 *Stream discharge and PO_4, P concentrations on the Naizin basin 7-8 March 1991*

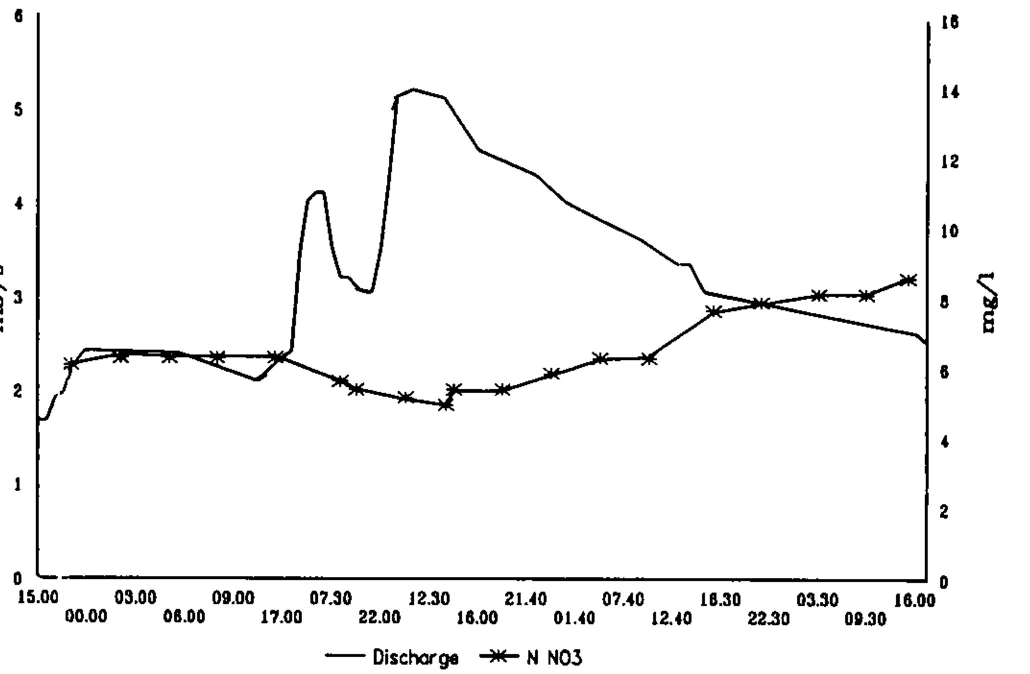

Figure 6 *Stream discharge and NO_3-N concentration in the Yar basin 8-13 January 1991*

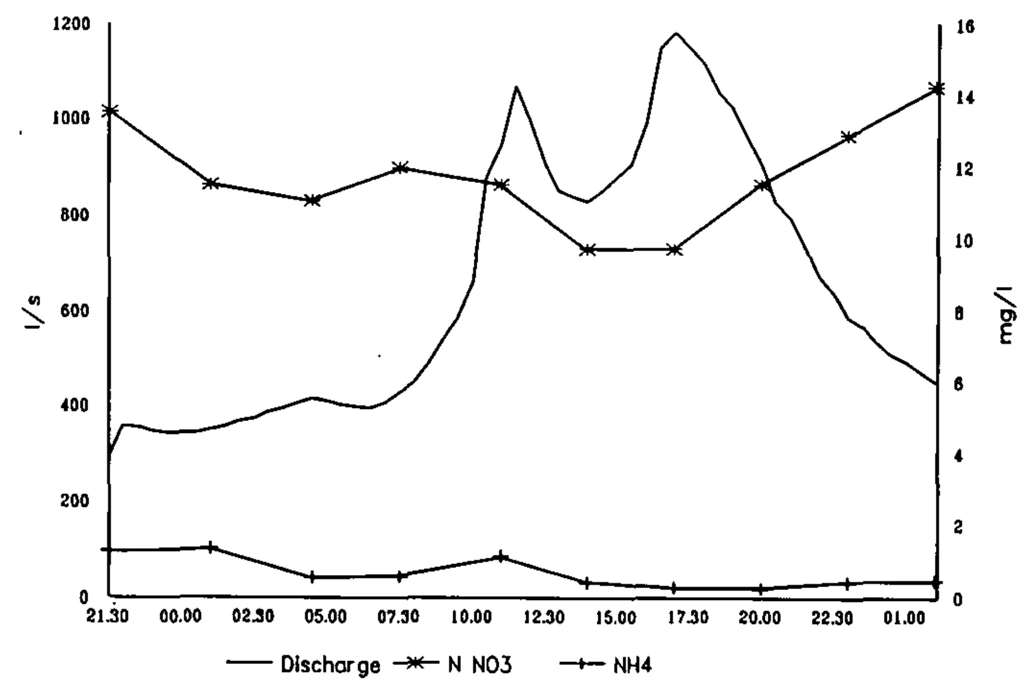

Figure 7 *Stream discharge and NO_3-N, NH_4 concentrations in Naizin basin 7-8 March 1991*

Each of these comparisons throw some light on the mechanism of water flow in soils and in the basin, but if a comparison is made of yearly nitrate flow and pig production on the Coet Dan basin, the correlation coefficient of the relationship between pig production and yearly mean nitrate concentration is not as good as might be expected. Rainfall can have a greater influence than agricultural productivity on nitrate flows, and that consequently many years of data are necessary to understand and quantify the influence of intensification on nitrate flows. During all the years spent on collecting data, intensification of agriculture has increased as can be seen by the comparison of results of the two surveys: 1988 - 1991.

A comparison of two basins such as Yar and Quillivarou would require less time to obtain meaningful results. However several years would still be necessary in order to collect data due to rainfall variability, differences of evaporation and so on. Moreover, there are always lots of differences between the physical characteristics of two basins and it is very difficult to eliminate the influence of these differences.

Last but not least, comparative studies on basins with such large anthropogenic effects is difficult since changes and variations in agricultural practice can occur differently on two catchments during the study.

Catchment comparisons give us very interesting results and, even better, different methods of comparison lead to the same kind of conclusions. Further, the interpretation of the differences of the results between the different ways of comparison can help us to understand the discharge mechanisms more precisely. Comparisons are necessary to study the spatial variation of the models which can be developed to describe water and solute transport: it is always necessary to spend many years collecting data before conclusions can be reached. Research on experimental and representative basins are always long-term projects.

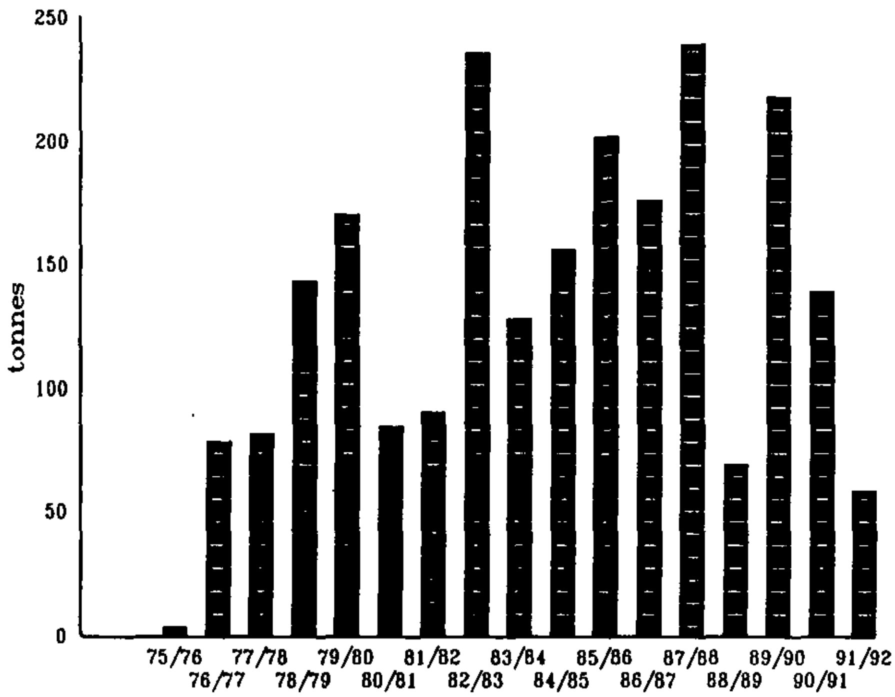

Figure 8 *Nitrate loads (tonnes) in streamflow from the Coet Dan basin*

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9. Paired basin studies on the Krofdorf Forest research area, Hesse/Germany

H.-W. Fuehrer

ABSTRACT

Calibration methods and preliminary results of a carefully planned experiment in the German low mountain range are presented. Stepwise timber cutting in a mature beech stand led to significant increases of annual runoff of up to 82 mm (29%). Annual runoff increases were detected by catchment comparison on the basis of a ten-year calibration period using linear regression technique.

The long-term records of stream water quality indicate some trends that are thought to be caused by acid deposition and soil acidification. Over 17 years of observation nitrate-nitrogen increased while the concentrations of the alkaline nutrients calcium and magnesium have been decreasing, especially in high flows. In this way small forest basins have proved to be well suitable for environmental monitoring ('benchmark catchments').

INTRODUCTION

In autumn 1971 a multiple catchment experiment was started in the Krofdorf Forest Research Area (KFRA). The control catchment approach (Reinhart, 1967) was used to study the possibilities of increasing water yield from beech forest by special treatment. In this connection water yield implies the three components water supply, streamflow timing, and quality of streamwater.

Four small forested catchments are being investigated with this objective. Cutting experiments were carried out in watersheds A1, A2, and the twin watersheds B1, B2 serve as references (Figure 1). The first ten years of the project (water years 1972 - 1981) were used for a systematic catchment calibration. Then in November 1982 the experimental cuttings began. In basin A1 the mature beech stands were removed stepwise over five years (water years 1983 - 1987) and regenerated both naturally and by supplementary planting. The mature beech stands in the lower half of catchment A2 are being regenerated naturally over a period of some 30 years, as is common forestry practice. The old-growth beech stands in the control basins B1, B2 remain untouched, with the exception of light thinnings that were carried out in winter 1981/82 in all four watersheds with equal intensity to minimize biological time trends of the past 10 years and to assure silvicultural stability for the subsequent years.

Several scientific institutions and authorities are working together in the KFRA. The project is well documented. Its methods and recent results have been published in detail already (e.g. Brechtel, *et al.*, 1982, Fuehrer, 1990, Fuehrer & Hueser, 1991, Brechtel & Fuehrer, 1991). This contribution mainly deals with some special methodical aspects and findings.

RESEARCH AREA AND METHODS

The KFRA is located 60 km north of Frankfurt/Main in the German low mountain range at elevations between 233 and 336 m above sea level. The climatic conditions are moderately subcontinental, with a mean annual precipitation of about 650 mm. Snow does not play a significant role on the temporal distribution of streamflow. The four investigated catchments (Figure 1) are characterized by similar site conditions, and importantly have a tight palaeozoic bedrock.

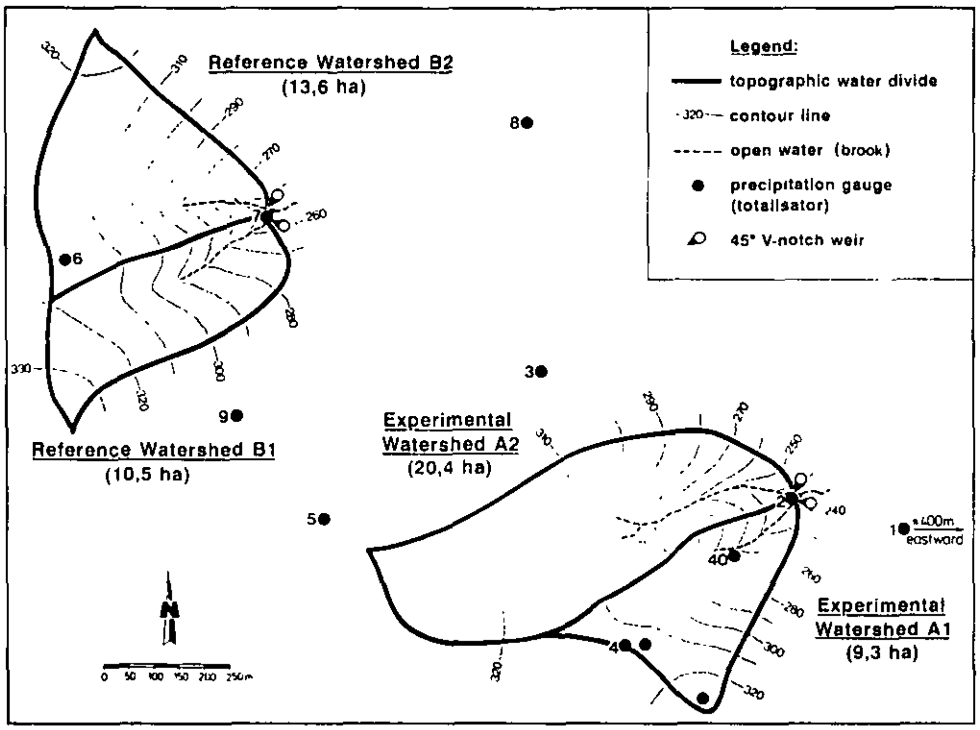

Figure 1 Catchment layout in the Krofdorf Forest Research Area (KFRA)

Precipitation is measured by numerous gauges distributed all over the research area (Figure 1) producing monthly total amounts. On the basis of these single-point measurements the areal precipitation is computed separately for A (= A1 + A2) and B (= B1 + B2). A continuously recording raingauge (type HELLMANN) installed two km south-western of the KFRA provides the temporal distribution of precipitation. Specially constructed 45° V-notch weirs having regard to experiences previously made in the U.S.A. (Reinhart & Piece, 1964) allow continuous recording of discharge on the four small brooks (Figure 1). For water balance purposes, soil moisture content was observed by monthly neutron probe measurements during selected periods.

The forest stocking of the four catchments had been very homogeneous before the experimental treatment in A1, A2. It had consisted mainly of old-growth deciduous hardwood stands (beech, *Fagus sylvatica* L., and some oak, *Quercus petraea* (Mattuschka) Liebl.).

For more detailed information on the KFRA, the experimental cuttings and their effects see the above mentioned project literature.

CALIBRATION METHODS AND CATCHMENT PECULIARITIES

Paired catchment studies using the control basin approach have proved to be the best and most suitable method to quantify the effects of management practices on water yield (Reinhart, 1967, Hibbert, 1967, Bosch & Hewlett, 1982). Taking into consideration the arguments of Kovner & Evans (1954), the Krofdorf project assigned a ten-year calibration phase (1972 - 1981) for the comparison of the two experimental basins A1, A2 with the two control basins B1, B2 before experimental treatment with respect to streamflow characteristics. The latter also includes water quality aspects which have been investigated by the Bavarian Forest Research Centre in Munich since May 1973.

After the calibration period Brechtel *et al.* (1982) reported on the streamflow relationships between the four catchments. Due to their similar site conditions very strong correlations were yielded. E.g. the R^2-value of mean annual streamflows amounted to 0.964 for the comparison A1 = f(B1) and 0.967 for the comparison A1 = f(B2). On this basis, annual runoff changes in any direction (two-sided test) for A1 will be statistically significant at the 95%-level if they exceed 54 mm using B1 and 44 mm using B2. Assuming that timber cutting only can increase runoff (one-sided test), any positive changes would be significant if they exceed 49 and 41 mm respectively (Fuehrer, 1990).

In addition to the control basin approach, multiple linear models predicting annual runoff in dependence upon different climatic parameters (as previously described by Eschner, 1965) have been computed. It proved that these models gave a much poorer statistical fit than the control basin approach. Their fitting demands more computation work. Furthermore, because of the high temporal variation of climatic parameters, the values in single years very often exceed the observed range. Hence these multiple relationships usually will be statistically well founded (Fuehrer, 1990).

The problem of exceeding the observed limits of the calibration period does occur in the streamflow comparison of the four catchments. For example the mean annual flows of B1, B2 in the water years 1983 and 1984 exceeded those in the calibration years 1972 - 1981 (Figures 2 & 3). In the case of the Krofdorf data this does not make the evaluation uncertain because the deviations within the extrapolated calibration relationships were only small. However, in principle the exceedance of flow values in the calibration period may raise severe troubles with respect to the scientific judgement of catchment experiments.

By chance the ten-year calibration phase in the Krofdorf project contained eight uninterrupted years with relative low precipitation (1972 - 1979, including the uncommon "dry" year 1976), see Fig. 4. The precipitation in only the two years 1980, 1981 exceeded the long-term average of about 650 mm. During the subsequent years the "wet" conditions continued. Hence there were two hydrologically distinct periods: the "dry" years 1972 - 1979 on the one hand and the "wet" years 1980 - 1988 on the other hand. Considering this precipitation distribution in the KFRA and our current common knowledge of long-term variations and cycles in precipitation development, it must be recommended to choose the calibration phase in paired/multiple basin studies as long as possible, independent from simple statistical demands.

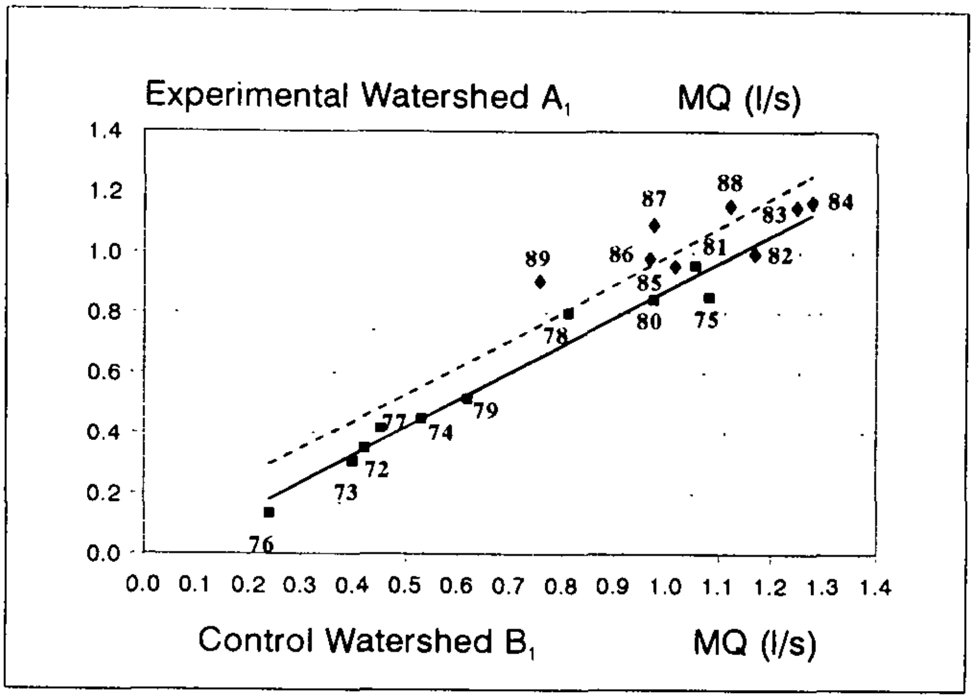

Figure 2 *Correlation of mean annual streamflows from basins A1 and B1.*
Solid line: regression line in calibration period 1972 - 1981
Dashed curve: 95% confidence interval for the one-sided hypothesis

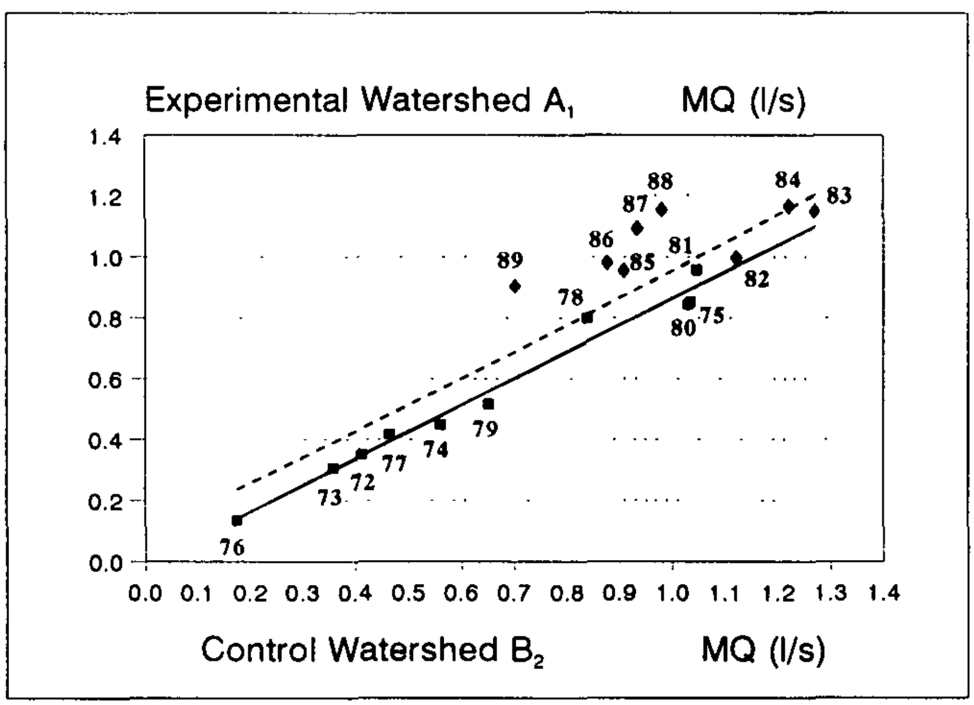

Figure 3 *Correlation of mean annual streamflows from basins A1 and B2.*
Solid line: regression line in calibration period 1972 - 1981
Dashed curve: 95% confidence interval for the one-sided hypothesis

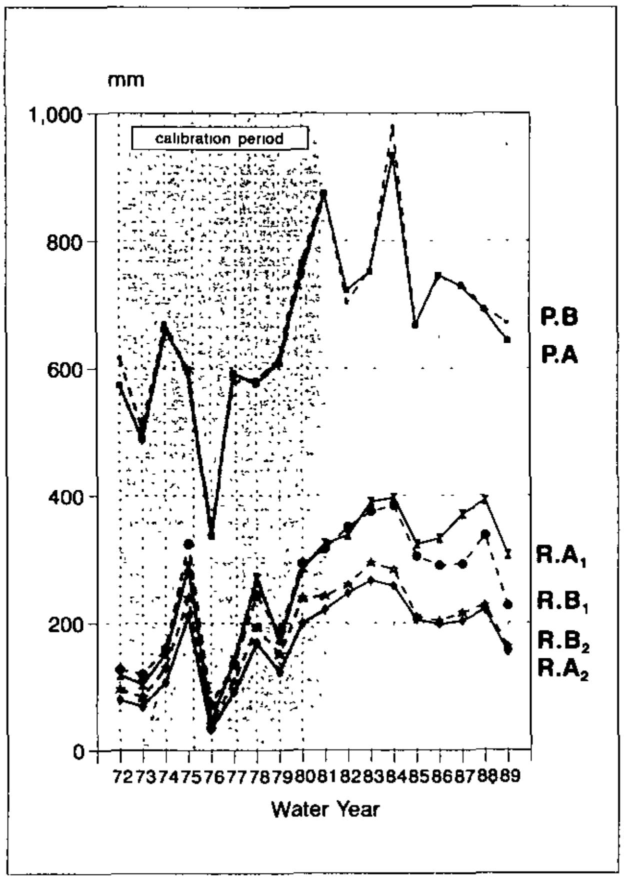

Figure 4 *Annual precipitation (P) for areas A and B and runoff (R) for the four basins*

Figures 2 and 3 indicate that the streamflow changes in the experimental watershed A1 are evaluated differently if they are compared with the individual control watersheds B1 or B2. The relation of A1 to B2 yields higher and more significant streamflow increases than the relation of A1 to B1 (Table 1). The reason is a somewhat different runoff behaviour of the two standards B1 and B2 upon the above mentioned time-trend in precipitation input. During the phase of uninterrupted "wet" years catchment B2 obviously has had some losses of deep seepage water that had not occurred during the former "dry" years (also see Figure 4). The conclusion must be that only B1 is a suitable reference watershed. The relation to B2 will probably considerably overestimate the effects on runoff from the experimental watersheds A1 and A2.

In this connection it has to be emphasized that the four catchments show different runoff quantities. This fact is illustrated well by the accumulated amounts of their precipitation-runoff-differences (Figure 5). During the calibration period, A1 and B1 behaved identically in this respect. In contrast A2 and B2 were characterized by lower amounts of runoff. In the second half of the 1980s the experimentally caused runoff increases of watershed A1 became evident. Considering the probable seepage water losses of the catchment B2, its curve in Figure 5 should have taken a somewhat lower course.

Table 1 *Surplus of runoff from basin A1 during the experimental phase as compared with control basin either B1 or B2, on the basis of calibration relationship (water years 1972 - 1981)*

Water year	A1 = f(B1)			A1 = f(B2)		
	mm	%	Statist. signif.	mm	%	Statist. signif.
1983	17	5	n.s.	16	4	n.s.
1984	13	3	n.s.	37	10	.95
1985	22	7	n.s.	58	22	.99
1986	46	16	.95	77	30	.999
1987	82	29	.99	98	36	.999
1988	61	18	.99	105	36	.999
1989	86	39	.99	103	50	.999

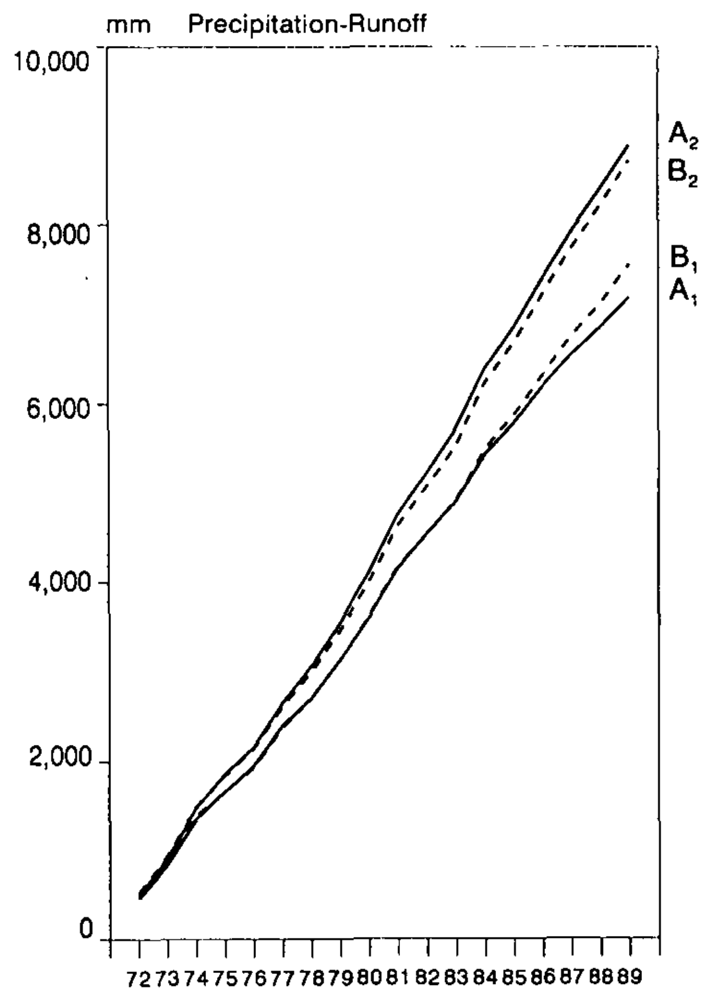

Figure 5 *Cumulative annual differences (precipitation minus runoff) for the four basins*

This partly different behaviour of the four catchments with respect to evapotranspiration and runoff can be explained to some extent by their individual topographic attributes. The watersheds A1 and B1 consist only of slopes while B2 and especially A2 also enclose almost plane parts in their upper elevations (Fig. 1). Under those conditions evapotranspiration rates might be higher, the more so since these plane parts of the watersheds A2 and B2 are partly forested with conifers instead of deciduous hardwood. Over that, deviations between the topographic and the phreatic water divide of course may also play some role especially in consideration of the small catchment sizes.

BENCHMARK CATCHMENT APPROACH

Besides the objective to quantify any effects of experimental cuttings upon water yield (for results from the KFRA see e.g. Brechtel & Fuehrer, 1991) long-term catchment studies are very useful for the detection of gradual changes on runoff and biogeochemical behaviour of forested ecosystems caused by the impact of air pollutants. In this connection the untreated control basins of the KFRA (B1, B2) can serve as "benchmark catchments" (Brechtel & Fuehrer, 1992).

Long-term increases of runoff for summer seasons as described for the Eyach catchment in the Black Forest of south-western Germany by Caspary (1990) using linear regression techniques did not yet occur in the KFRA. However, there are some gradual changes on streamwater quality (Fuehrer & Hueser, 1991; see Fig. 6) that also might be pointed to here.

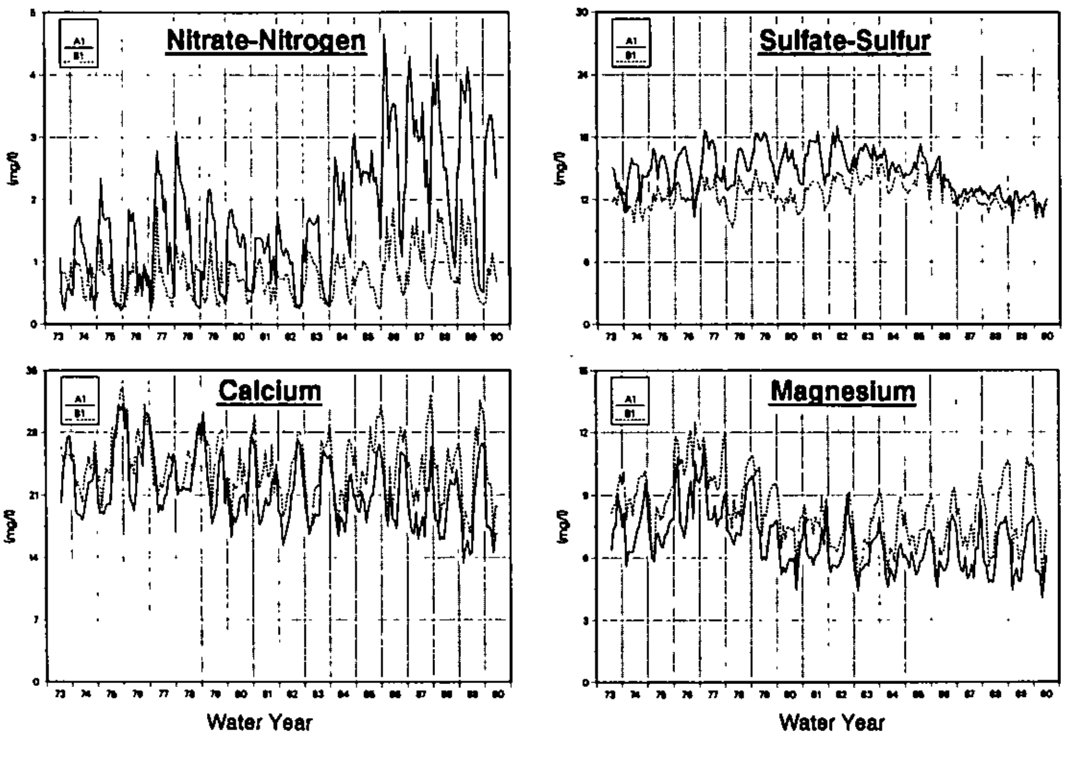

Figure 6 *Mean monthly streamwater concentrations of NO_3-N, N, SO_4-S, Ca and Mg from basins A1 (treated) and B1 (untreated 'benchmark') from May 1973 - April 1990*

As illustrated by Figure 6 the activity of nitrate-nitrogen in streamwater has been increasing during the second half of the 1980s. Sulfate-sulfur has been decreasing since 1984, due to some reduction of the SO_2- emission rates in Western Germany. The concentrations of calcium and magnesium cations showed decreasing tendencies, too, especially with regard to the annual minimum values from 1976 until 1990 which usually occurred during the high flow periods of the winter season.

These trends are supposed to indicate a relatively rapid progress of soil acidification. In this, however, the special hydrological circumstances since 1972 must be taken into consideration, too. Hence Figures 7 and 8 show a temporal comparison of the stochastic concentration-discharge relationships for nitrate-nitrogen and magnesium in control watershed B1 between the calibration phase and the subsequent years. The further development of these features in the KFRA benchmark catchments will be of great interest.

With regard to the 95% confidence limits of the calibration relationships, the relative changes in nitrate-nitrogen concentrations are considerable, especially at low flows, and for magnesium especially in high flows. This might indicate an increasing and deeper penetration of nitrate within the soil and a rapid decrease of the exchangeable magnesium storage in the main root compartment, due to the steady input of nitrogen and acids from the atmosphere.

CONCLUSIONS

The recent investigations carried out on the KFRA have made several important findings with regard to the methodology of paired catchment studies:

(a) Several reference basins should be used if possible. In case of only one control basin there is a high risk of choosing an unsuited standard, even if the site conditions of the compared basins are quite similar. This holds true especially for very small catchments (< 50 ha).

(b) The duration of the calibration period should be determined not simply by statistical demands. It has proved to be important that calibration include not only single years with low and high precipitation, but also sequences of some dry and wet years.

(c) The control basin approach based on an appropriate reference object has once more proved to be the best and most efficient technique for catchment calibration purpose.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the substantial contribution of the chair of soil science at Munich University and the Bavarian Forest Research Centre to the Krofdorf project. They are investigating the bioelement input and output of the KFRA catchments. All chemical analyses presented here have been made in their laboratory.

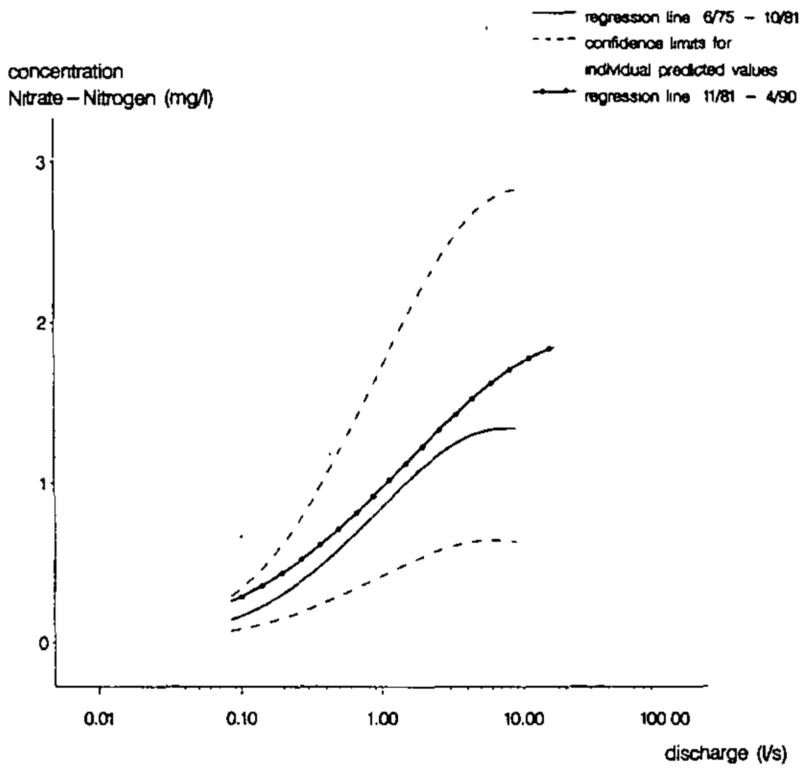

Figure 7 *Streamwater concentrations of NO_3-N and discharge for control basin B1, during different time periods*

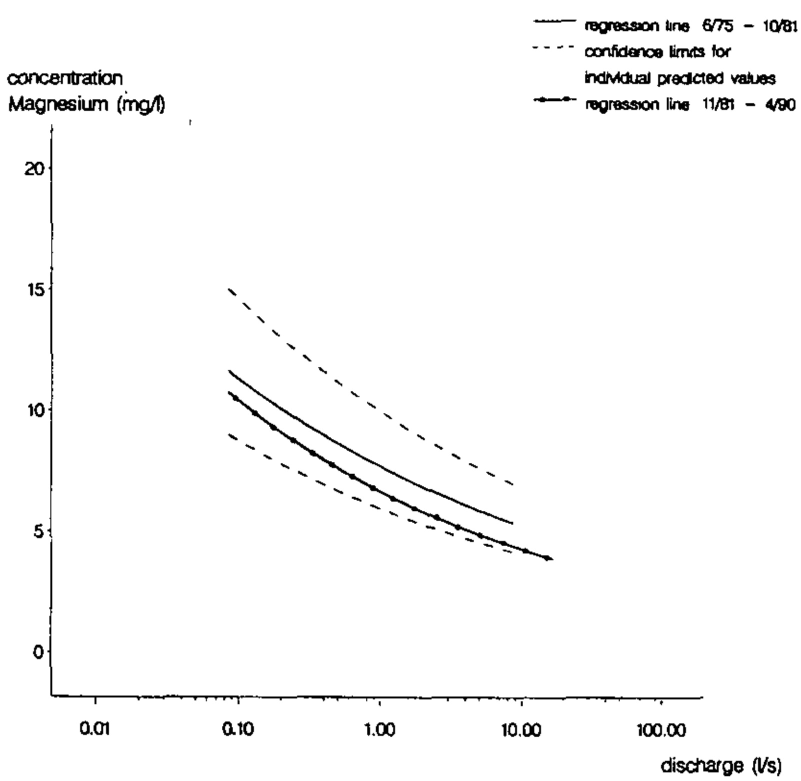

Figure 8 *Streamwater concentrations of magnesium and discharge for control basin B1, during different time periods*

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10. A scale-dependent approach to the study of nutrient export from basins

T. P. Burt & A. L. Heathwaite

ABSTRACT

Slapton Ley is the largest natural body of freshwater in south west England. Since the 1960s there has been much concern that the lake is becoming increasingly eutrophic. From 1969 a monitoring programme has been maintained to quantify runoff, sediment and solute inputs into the lake. In addition, a number of experimental studies have sought to link runoff processes to the loss of sediment and nutrients from the catchments. This paper reviews those studies concerned with losses of nitrogen and phosphorus from the Slapton Ley catchment.

SEDIMENT AND SOLUTE DELIVERY

An increased awareness of the role of agriculture in non-point source pollution has stimulated the need for information on the effect of agricultural management practices on surface water quality. Given the easier identification and control of point sources of pollution, it is likely that diffuse pollution from agricultural sources has now become the most significant origin of pollutants in many rural catchments. It is therefore necessary to develop models that simulate sediment and nutrient transport in order to help select management systems which can minimise associated water pollution problems. Field experiments which identify the mechanism of pollution transport in agricultural catchments provide crucial support for this process.

In headwater catchments, the pattern of outflow production is strongly related to runoff production at the hillslope scale. Precipitation is divided between various flow routes which attenuate and delay the flow to different extents; in addition - and most importantly from the point of view of nitrate and phosphate export - the quality of precipitation may be greatly modified depending on its hydrological pathway. Any analysis of sediment and solute transport should therefore begin with consideration of runoff processes. However, despite great interest in hillslope hydrology over the last three decades, there is still surprisingly little evidence that can be used to relate small catchments, where hillslope runoff generation is the dominant hydrological mechanism, to the flood response of large basins (Burt, 1989). Though the use of distributed models is beginning to help with respect to water quantity, we have much less ability to relate sediment and solute production at the hillslope scale to water quality at the basin outlet.

Information on sediment and solute yields measured at the basin outlet has been widely used as a basis for assessing losses from the catchment area. Such information clearly has potential advantage in providing estimates of average loss rates representative of sizeable areas and therefore in avoiding the need for spatial sampling (Walling, 1990). However, much caution is needed in any attempt to interpret yield data in terms of catchment losses. Walling (1983, 1990) has emphasised the problems involved in taking account of the processes of sediment delivery interposed between on-site erosion and downstream sediment yields. It is well known that only a proportion, perhaps rather small, of the soil eroded within a catchment finds its way to the basin outlet. Temporal discontinuities in sediment conveyance may exist. The amount of sediment transported out of a basin may reflect past rather than present patterns of erosion. Seasonal variations in land cover and climate may cause large variations in erosion rates which may or may not be reflected in the basin outlet. Spatial variations in erosion within the catchment mean that average yields for the catchment may bear no relation to local erosion rates. Given its relative insolubility, phosphate loss is likely to be strongly related to soil erosion in the first instance. Even so, it is clear that there are likely to be numerous uncertainties involved in relating phosphate losses from hillslopes to phosphate yield at the basin outlet. Further difficulties are introduced because phosphorus is subject to a number of physical and biochemical interactions during its transfer through the basin. These include adsorption of soluble forms onto suspended sediment, assimilation by microorganisms, and changing solubility controls in relation to water pH (Heathwaite & Burt, 1991).

Relative to sediment transport, rather less attention has been paid to the concept of solute delivery. It might be thought that solute delivery would be easier to understand than sediment delivery, given the relatively simple link between solute transport and water flow, compared to sediment movement where flow velocity controls particle movement in a much more complex manner. However, the two topics are more similar than we might think. Solutes, too, are subject to transformation and storage during their passage through the basin. For example, Haycock and Burt have studied nitrate losses in groundwater flowing through riparian zones, whilst Vannote *et al.* (1980) and Elwood *et al.* (1983) have emphasised nutrient cycling in lotic systems. Naiman & Décamps (1990) provide a general review of solute processes in terrestrial-aquatic ecotones. Thus, despite the dependence of sediment movement on surface runoff and of solute movement on subsurface flow, we may expect to find that, in both cases, there is no simple link between rates of removal from the soil and measured losses at the basin outlet. It is interesting to note in passing that both topics have been studied in a similar manner in the past with more emphasis on soil loss (as demonstrated, for example, by preoccupations with the Universal Soil Loss Equation and with nitrate leaching models) and on estimating losses at the basin outlet. In both cases, at least until recently, conveyance processes through the basin have been relatively neglected. This paper offers some small contribution to the recent debate by contrasting patterns of nitrate and phosphate export from small agricultural basins. The need for a scale-dependent approach is emphasised but, given the preliminary stage of the investigations, a large number of linkages in the delivery process remain poorly understood.

The relationship between nitrogen (N) and phosphorus (P) loading and eutrophication remain uncertain. In Britain, most fresh water bodies appear to be P limited for most or all of the year though N may be limiting where P inputs are high or in late summer when N inputs are particularly scarce and microbial uptake is high. In estuaries, denitrification and release of P from sediments may mean that waters are N limited (Birch & Moss, 1990). However, since almost all eutrophication problems seem to be associated with increases in both N and P, it remains highly relevant to study the delivery of both nutrients through the drainage basin system. Most emphasis has been given to N, especially nitrate, in recent years. It now seems timely to stress the importance of P. Our research within the Slapton catchments has provided the opportunity to consider both N and P within a single study.

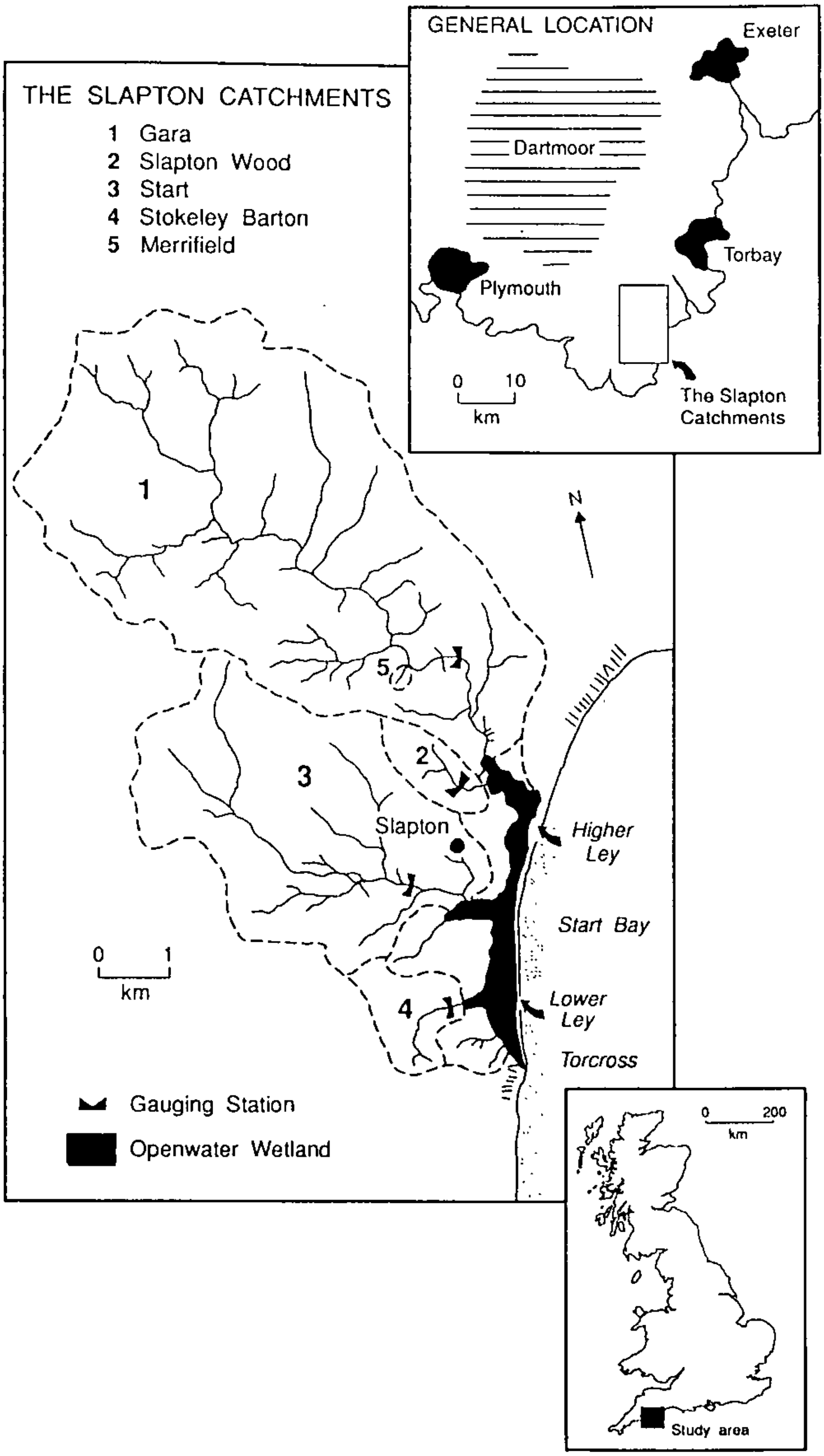

Figure 1 ***The Slapton catchments draining into the freshwater lake, the Slapton Ley***

SITE DESCRIPTION

Slapton Ley is a coastal lake in south Devon, England (UK National Grid reference SX 825479). It is the largest natural body of fresh water in south west England and is an important nature reserve, soon to be accorded National Nature Reserve status. The Ley may be divided into the Higher Ley, a 39 ha reedbed system and the 77 ha Lower Ley, an area of open water fringed by reedbeds. 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 area of Slapton Ley (46 km^2) may be divided into four subcatchments (Figure 1 and Table 1); the gauged area of each together comprise 82% of the total. Ungauged areas plus minor basins which drain directly into the Ley account for the remaining 19%. Topography consists of wide plateaux dissected by narrow, deep valleys (maximum slope angle 25°). The land rises to over 200 m altitude in the northern part of the basin, which is drained by the River Gara, the largest of the subcatchments. The catchment is underlain by impermeable Lower Devonian slates and shales. Soils are acid brown earths, less than 1 m deep on steep slopes but over 3 m deep in valley floors. Being silty clay loam in texture, the soils are naturally permeable but are easily compacted by livestock or heavy machinery. Land use in the Gara basin is mainly permanent pasture and temporary grass with the lowest proportion of arable land. Further south, lower altitudes and gentler slopes allow the development of mixed farming with one third of the area in the Start catchment under arable cultivation (Johnes & O'Sullivan, 1989).

Mean annual rainfall (1961-88) at the Slapton Ley Field Centre is 1039 mm; Van Vlyman (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 120° 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). Mean annual temperature at the Field Centre is 10.5°C.

RESULTS - A SCALE-DEPENDENT APPROACH

Plot Experiments

In order to quantify the production of surface runoff, suspended sediment and nutrients from different land uses, a series of plot experiments were conducted using a rainfall simulator (Heathwaite *et al.*, 1990 a, b). The results (Table 2) show that surface runoff from heavily grazed permanent pasture was double that from lightly grazed areas and about twelve times that from ungrazed temporary grass. Large amounts of runoff were also produced from soil which had been compacted by rolling (to produce a fine tilth after seed had been drilled). The largest losses of sediment and nutrients came from the heavily grazed pasture; losses of P were mainly organic while over 90% of N was lost as ammonium. Nutrient losses from the lightly grazed pasture were much less but again organic losses of P were relatively high and inorganic N was lost largely as ammonium. There was much less runoff from the ungrazed temporary grass and from the cereal field; in both cases a much larger fraction of P was lost in inorganic form. There was a large loss of sediment from the bare ground but nutrient losses were quite low; N was lost in roughly equal amounts as ammonium and nitrate. The results suggest that heavily grazed land may be the source of high nitrogen, phosphorus and suspended sediment inputs to the stream system through surface runoff. Much depends on the

Table 1 *Slapton catchments: land use and nutrient loads for the 1988 water year*

	Gara	Slapton Wood	Start	Stokeley Barton
Area (ha)	2362	93	1079	153
Runoff (mm)	920	581	950	148
Land Use(%):				
Grass	81.2	32.1	52.6	28.8
Arable	11.9	36.1	34.2	66.0
Stream loads ($kgha^{-1}$) total load (t) is given below in brackets:				
Ammonium-N	1.79 (4.2)	0.16 (0.02)	1.39 (1.5)	0.23 (0.03)
Nitrate-N	68.03 (160)	63.60 (5.9)	103.93 (112)	19.51 (3.0)
Phosphate-P	0.38 (0.9)	0.21 (0.02)	0.58 (0.6)	0.21 (0.03)
Suspended sediment	503.34 (1190)	66.15 (6.21)	224.89 (242)	23.37 (3.6)

Table 2 *Runoff, sediment, nitrogen and phosphorus production from hillslope plots. All rainfall simulation experiments lasted 4 hours at an intensity of 12.5 mm hr^{-1}*

	Heavily grazed permanent grass	Lightly grazed permanent grass	Temporary grass	Cereal (after harvest)	Bare ground (after rolling)
Total runoff (mm)	26.5	11.6	2.3	2.7	10.6
Sediment (g)	22.28	0.37	0.15	0.31	5.10
Sediment per unit runoff (mg mm^{-1})	840	31	65	84	481
Total P (mg)	124.63	3.33	0.73	0.76	1.87
Total P per unit runoff (mg mm^{-1})	4.70	0.29	0.32	0.21	0.18
Inorganic P (mg)	21.45	2.00	0.33	0.35	0.49
Inorganic P per unit runoff (mg mm^{-1})	0.81	0.17	0.14	0.09	0.05
Total N (mg)	69.63	2.96	nd	nd	3.40
Total N per unit runoff (mg mm^{-1})	2.64	0.26	nd	nd	0.32
Inorganic N (mg)	64.15	0.81	nd	nd	0.82
Inorganic N per unit runoff (mg mm^{-1})	2.42	0.07	nd	nd	0.08

nd = not detectable

infiltration rate associated with the particular land use at any one time. Large losses of sediment and nutrients from grazed land may be especially important where such land is located adjacent to a stream. Losses of P from bare ground are small, despite the large loss of sediment; even so, rates of soil erosion in the Slapton Catchments are sufficiently high that soil-bound P is still an important fraction of the total P loss from the area (see below).

There have been no bounded plot (lysimeter) studies of nitrate leaching within the Slapton catchments, therefore subsurface flow pathways have not been examined in detail. Profile studies of soil moisture and soil nitrate have been conducted using tensiometers and suction cup lysimeters. Coles & Trudgill (1985) used unbounded plots and ^{15}N to show 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.

Hillslope studies of nitrate loss

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, and all areas of the catchment are significant sources of non-point subsurface inputs. In the Slapton Wood catchment, nitrate losses from five hillslope units 8-20 ha in area were clearly related to land use (Burt & Arkell, 1987):

1	Headwaters	(mainly arable)	48.41 kg $ha^{-1}year^{-1}$
2	Valley side slopes	(arable and grass)	44.56 kg $ha^{-1}year^{-1}$
3	Carness hollow	(arable and grass)	33.17 kg $ha^{-1}year^{-1}$
4	Eastergrounds hollow	(grass)	31.63 kg $ha^{-1}year^{-1}$
5	Slapton Wood	(woodland)	23.91 kg $ha^{-1}year^{-1}$

However, Trudgill *et al.* (1991a) were unable to demonstrate clear relationships between soil nitrate content and land use or between soil nitrate and leaching loss. Leaching losses appear to relate more to the generation of subsurface flow in relation to soil and topography than to land use alone. These results suggest strongly that an integrated approach is required combining plot and hillslope scale observations. It is clearly not a simple matter to relate soil conditions to patterns of leaching from a hillslope, nor to infer leaching mechanisms from flow observations at the foot of a slope.

Sediment and nutrient losses at the catchment scale

Table 1 shows the inorganic stream load for the 4 catchments for the 1988 water year. These data were computed from continuous discharge observations and from water samples taken at intervals ranging from 15 minutes during storm events to a maximum of 24 hours. For the two largest catchments, Gara and Start, high loads are shown for all variables. The Gara has a particularly high suspended sediment load which may be related to its steep slopes; relatively high losses of ammonium in comparison with the other subcatchments suggest that grazing may be an important factor. The Start has a high inorganic N and P load which may relate to the greater amount of arable land in this catchment.

It is clear, however, that much caution must be shown when interpreting yield data in terms of upstream conditions. Ideally, observations from representative plots and hillslopes are needed to supplement the yield data. It would also be preferable to measure total N and P losses, not just the inorganic fractions, since the organic load may comprise an important part of the total load (see below).

The majority of the annual stream load is delivered in winter when discharge is high; usually loads peak in January and February. In the 1988 water year, 64% of the nitrate load in the Gara and 54% of the nitrate load in the Start were delivered in these two months (Heathwaite *et al.*, 1989); similar results were found by Burt & Arkell (1987). Nitrate concentrations on the Start exceeded the EC limit for four months. For suspended sediment, 93% and 70% of the Gara and Start load were delivered in January and February, a period when surface runoff production was at a maximum. The winter load of ammonium and phosphate, being strongly related to the sediment transport, also peaked in those two months, about 70% of the annual load in both cases.

The lake: source or sink for sediment and nutrients?

The impact of stream loads on lake water quality is determined by the ability of the lake to assimilate the inputs. The Higher Ley is a sediment trap for material eroded within the Gara and Slapton Wood catchments; partly as a result of this, it also acts as a nutrient source in summer (see below). No measurements of sedimentation rates have been made in the Higher Ley. Heathwaite and O'Sullivan (1991) discuss the history of sedimentation in the Lower Ley and Owens (1990) has examined deposition in the lower Start valley.

The Lower Ley has a flushing rate of 20 times per year (Van Vlymen, 1979), but in winter at peak flow, the lake volume is replaced every three days. This suggests that a large proportion of the stream load will be displaced from the lake in winter, thus having little impact on eutrophication. It is in summer, when the flushing rate is low, that stream inputs are most important; moreover, nutrient cycling within the lake water and the release of nutrients from lake sediments also becomes significant at this time. Table 3 shows the monthly sediment and solute balance for the Higher Ley for the 1988 water year. The Higher Ley acts as an important sink for sediment and nutrients in winter, but functions as a source during the summer when flow is low and when pH/Eh conditions at the sediment-water interface may favour release of nutrients, especially P (Heathwaite & Burt, 1991). For the 1988 water year as a whole, the Higher Ley was an important sink for ammonium, nitrate and suspended sediment, but a source of inorganic P. It may well be that the transformation of soluble P, originally bound to soil particles, into more available forms is an important factor in the eutrophication of the Ley. However, more work is needed to investigate the changing roles of N and P within the lake water through the summer season. On occasions, nitrate concentrations fall in very low levels (Heathwaite, 1989); under such conditions, albeit temporary, N rather than P may be the limiting nutrient. Once again, the need for complete N and P budgets must be seen as a goal for future research.

Comparisons with modelling results

Johnes and O'Sullivan (1989) have used an export coefficient model to predict N and P losses from the Slapton Ley catchment. Their results are shown in Table 4 together with our own measurements of inorganic N and P inputs into the lake. There is reasonable agreement between the figures, but the lack of total N and P loads is again a weakness.

Heathwaite and Burt (1991) have used the same export coefficient model to examine the effect

Table 3 *Input-output budget for the Higher Ley*

	Ammonium-N			Nitrate-N			Phosphate-P			Suspended sediment		
Month	I	O	B	I	O	B	I	O	B	I	O	B
Oct	0.19	0.012	+0.178	6.17	0.46	+5.81	0.037	0.006	+0.031	32.7	0.1	+32.6
Nov	0.57	0.058	+0.512	18.96	6.67	+12.29	0.097	0.021	+0.076	198.2	1.5	+196.6
Dec	0.32	0.046	+0.274	14.88	7.64	+7.24	0.024	0.014	+0.038	765.0	1.8	+74.2
Jan	1.35	0.046	+1.304	63.75	13.92	+49.83	0.304	0.048	+0.256	520.2	7.4	+512.8
Feb	1.20	0.227	+0.973	42.91	24.54	+18.37	0.159	0.128	+0.031	198.3	56.3	+142.0
Mar	0.30	0.119	+0.181	7.75	4.63	+3.12	0.114	0.650	-0.536	119.9	13.9	+106.0
Apr	0.09	0.139	-0.049	7.99	4.73	-3.26	0.044	0.661	-0.617	15.7	15.1	+0.6
May	0.07	0.080	-0.010	2.90	3.22	-0.32	0.042	0.038	+0.004	7.3	14.2	-6.9
Jun	0.01	0.047	-0.037	0.90	0.80	+0.10	0.014	0.016	-0.002	1.4	2.3	-0.9
Jul	0.06	0.077	-0.017	0.87	0.33	+0.54	0.038	0.017	+0.021	6.1	2.2	+3.9
Aug	0.01	0.002	+0.008	1.02	0.58	+0.44	0.013	0.008	+0.005	6.8	1.6	+5.2
Sep	0.05	0.038	+0.012	1.64	1.19	+0.45	0.021	0.077	-0.056	12.4	0.7	+11.7
Year	4.21	0.891	+3.324	166.58	71.97	+94.61	0.907	1.684	-0.777	1195	118	+1078

All figures in tonnes; I = input; 0 = output; B = balance

Table 4 *Nitrogen and phosphorus losses (t) from the Slapton catchment. Modelling results from Johnes and O'Sullivan (1989). Measured losses based on Table 2 and multiplied by 1.23 since only 81% of the catchment area is gauged; note that Slapton sewage works is not included within the gauged area*

	Nitrogen	Phosphorus
(a) Model results:		
Loss from farmland		
inorganic	56.15	0.46
organic	91.65	1.98
Total	147.80	2.44
Loss from woodland	2.27	0.02
Human contribution	8.00	2.33
Total	158.07	4.79
(b) Field measurements (x 1.23 to account for ungauged area):		
	352.58	1.55

of land use change during the twentieth century on water quality in Slapton Ley. Sediment cores from the lake (Heathwaite & O'Sullivan, 1991) and water quality records from 1970 provide verification for the model results. The model accurately predicts total N losses from the catchment, but underestimates nitrate concentrations, probably because organic N is readily transformed into inorganic N during its passage through the hydrological system. A significant increase in stream nitrate levels has been recorded over the last 20 years (Burt *et al.*, 1988). Statistical analyses and the modelling results both suggest that changes in agricultural practice, rather than climatic variability, are responsible for the observed increase in nitrate concentration. Only a small component of the increase can be related to human sewage (see Table 4). In contrast, the human contribution to P inputs may be more important, though as Acott (1989) and results on Table 4 show, losses from farmland still account for about half of the P losses. Furthermore, known inputs of phosphorus to the drainage network from the Slapton sewage works account for less than 2% of the annual input of PO_4^{3-} to the Lower Ley (Heathwaite & Burt, 1991). Like N, P losses from agricultural land have increased very significantly through the twentieth century and especially since the 1950s. As a result of these catchments inputs, the lake is now hypereutrophic (Heathwaite & O'Sullivan, 1991). Johnes and O'Sullivan suggest that control of P losses from sewage will not be sufficient to reduce nutrient inputs to the Ley to acceptable levels and that some attention will have to be paid to losses from farmland too.

CONCLUSIONS

It is apparent that an integrated experimental design is required to study the conveyance of sediment and nutrients to the stream channel if the uncertainties inherent within the sediment delivery system are to be solved. It is clear too that, as far as N and P losses are concerned, total budgets are required, not just certain species (usually, only the inorganic fraction is available). There are, however, many difficulties involved in such experiments, not least the cost and effort needed.

The data from the Slapton catchments confirms that input water is enriched in both N and P. It seems likely that P is commonly the limiting nutrient, but N may well be limiting at times during the summer. Sediment inputs from the Start and Gara basins are the cause of some concern, partly because of its rapid and consequent effect on wetland habitats, but mainly because the sediment is an important source of P which may be mobilised if conditions are appropriate at the sediment-water interface. In the short term, control of sewage inputs (mainly P) may help prevent the level of eutrophication from becoming worse, though Trudgill *et al.* (1991b) suggests that P might continue to be mobilised from a marsh long after sewage inputs to the marsh have been eliminated. In the longer term, land use controls to limit both N and P losses from farmland may be necessary, though this may only be profitable (in the economic sense) if financial compensation is available to farmers. The need for a more integrated approach to catchment planning, as a means of managing water quality, is discussed in more detail by Burt & Haycock (1992).

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11. Representative catchment scale from a geochemical point of view

Ph. Merot & P. Bruneau

ABSTRACT

Simultaneous variations of chloride (Cl^-) and nitrate (NO_3) concentrations were recorded in a 570 ha catchment and 4 sub-catchments. The smaller the catchment, the weaker is the dependence of nitrates concentration on the water cycle. On the basis of the data, a representative elementary area of about 100 ha is defined for the studied site.

INTRODUCTION

The definition of the appropriate catchment size for hydrological studies is under constant discussion. The notion of a representative catchment area, based on physiographic characteristics, has often been defined from an empirical point of view. De Marsily (1990) criticizes the notion of representativity, because hydrologists are not able to find an emergence of specific properties at a macroscale. Recent work, in line with current attempts to rebuild hydrology on a more scientific basis (Bowles & O'Connell, 1991; Klemes, 1986), provides some answers: research in the field often takes into account the spatial variability of natural systems at various scales (e.g. Vachaud, 1989); similarly, theoretical efforts, often based on modelling, take into account scale and spatial structure (Rodriguez-Iturbe & Valdes 1979; Sipavalan *et al.*, 1987).

Currently, Wood *et al.* (1990, 1988) are attempting to built a theoretical framework for the understanding of small-scale variability and storm response at the catchment scale. The concept of the Representative Elementary Area is used in a manner similar to the Representative Elementary Volume in soil physics (Bear & Jacob, 1972).

This paper contributes to the analysis of the representativity of a catchment at a specific scale, based on geochemical data.

MATERIALS AND TOOLS

Hydrological measurements were carried out on a 570 ha catchment, on granite, in an intensive farming zone (Geng, 1988). The concentrations in NO_3 and Cl^- were measured each month at the outlets of 4 sub-catchments with different areas (basin D, 20 ha; B, 23 ha; A, 66 ha; E, 365 ha) and of the whole catchment (basin R). The paper is based on data over one year. Chemical measurements were made with an HPLC.

The catchment and the four sub-catchments (Figure 1) are described in detail from the following points of view: topography, using a digital elevation model; soil cover; the main features of the landscape, especially the existence of a network of hedgerow banks. The soil occupation and the farming practices were investigated, focusing on chemical and organic

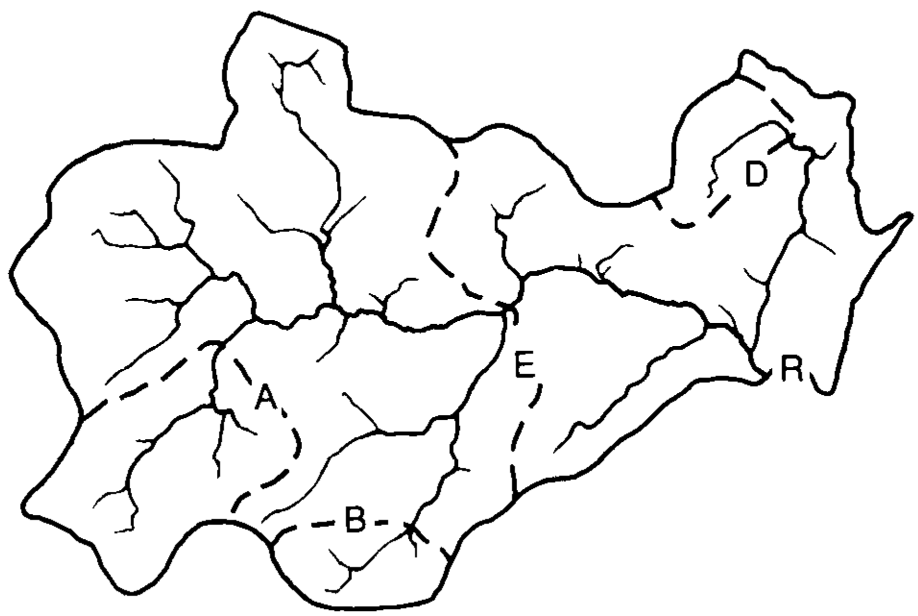


Figure 1 *The study catchment and its four sub-catchments*

inputs and outputs. Factors with an impact on the nitrogen cycle were emphasized (Mariotti, 1986; Merot & Bruneau, 1993; Pinay *et al.*, 1989). This is approximately the same level of fertiliser application over all the catchments.

A comparative study of the variations of Cl^- and nitrates was performed. Cl^- was chosen as an environmental tracer of the water cycle, indicating movement of the water (Ambroise, 1992; Pinder & Jones, 1969): the Cl^- content is due to the mixing of different reservoirs with different Cl^- concentrations in the catchment, mainly groundwater with a noticeable and constant concentration of Cl^-, and less concentrated surface water. Therefore, the Cl^- variations in the river are due to varying amounts discharged from reservoirs.

Variations in nitrogen content are due to the input-output budget, the different processes of the nitrogen cycle, and the movement and dilution of the water. If the latter are predominant, a strong negative correlation is found between variations of nitrates and Cl^- content.

RESULTS

Variation of Cl^- and nitrates in time

Figure 2a shows the variations of Cl^- concentrations at the different basins. The catchments R, A, and B have similar contents and variations. The concentrations of catchments D and E vary slowly and independently of the other catchments.

Nitrates concentrations in the water show a large heterogeneity between the different plots as well as at a given plot at different times (Figure 2b). The different modalities of nitrates content variations in time between the catchments can be more easily compared with normalized data: the nitrates concentration of the different samples of a catchment is divided by its own mean concentration during the winter of 1990-91 (Figure 3).

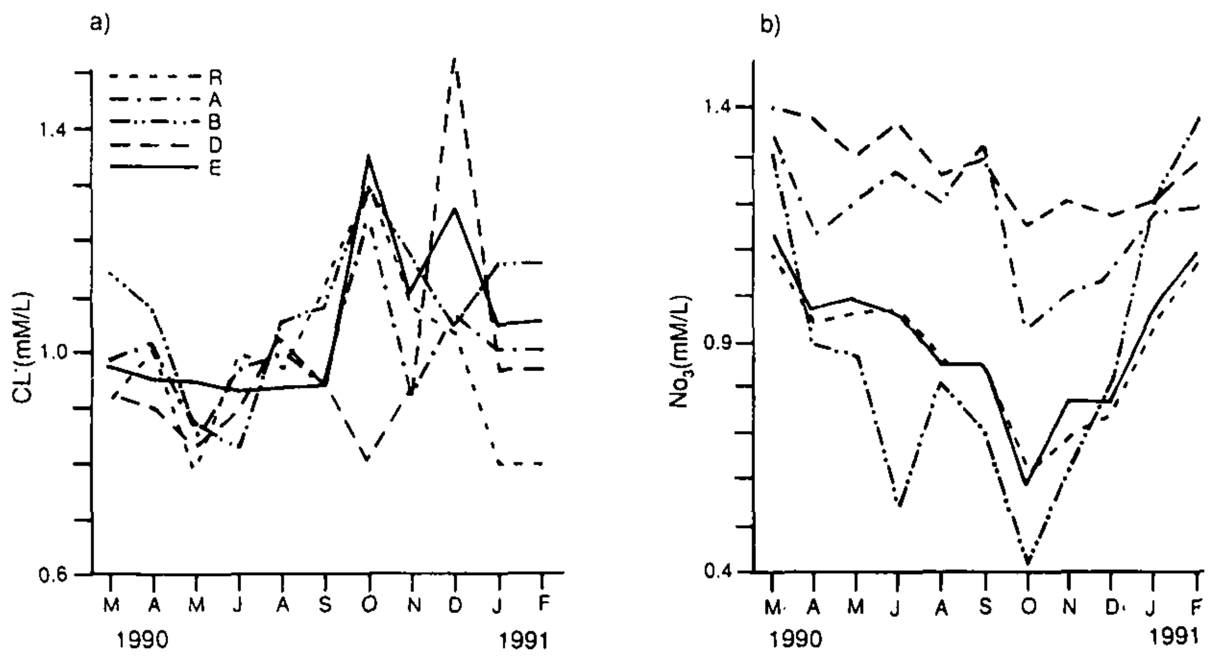
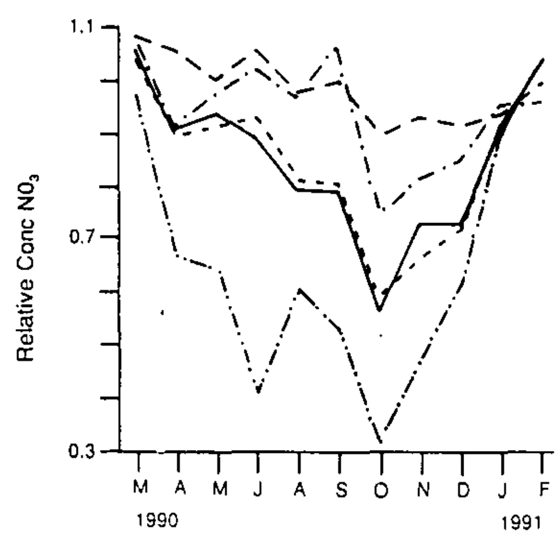


Figure 2 *Streamwater concentrations of a) Cl^- and b) NO_3^-. There are no data for July*



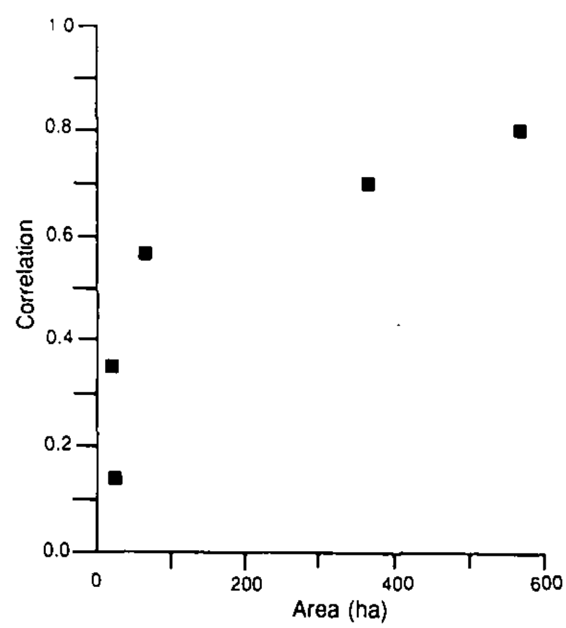


Figure 3 *Relative NO_3^- concentrations (sample concentration/mean winter concentration)*

Figure 4 *Relation between the correlation coefficient between Cl^- and NO_3^- concentrations and basin area*

The variations of nitrates content in the different catchments are simultaneous; there is a depletion from spring to autumn when the nitrates content is at its minimum. The nitrates concentration is at its maximum in winter time. However, the variation lag is different for each catchment. Basin B shows the largest variations, basin D the smallest; the variation of E and R are similar. The variations for A, C, R, E are contained between the variation for the basins B and D.

Comparison of variations in Cl^- and nitrates

The relationship between point concentrations of Cl^- and nitrates was examined for each catchment. The correlation coefficient is negative and varies from 0.14 to 0.80, depending on the catchment. A noticeable relation appears only for catchments R and E. When the correlation coefficient is plotted against the area of the catchments (Figure 4), it appears that the coefficient increases with the size of the area.

DISCUSSION

According to the Cl^- concentrations, catchments R, A and B share the same hydrological processes, while catchments D and E show some differences. The variability of nitrates concentrations seems hard to explain both as concerns the concentration level and the characters of the variations in time, specific to each catchment. Therefore, the catchment B, that has an important depletion in nitrates during summer and autumn, presents some specific features supporting denitrification: bottom lands often saturated, hydromorphic and peaty soils with permanent pastures, surrounded by a hedgerow bank.

The analysis of the relative variability of Cl^- and nitrates makes it possible to study the effect of the hydrological control of the variations in nitrates content: the nitrates concentration seems to be linked to the hydrology of the 570 ha catchment, whereas this relation disappears for areas of less than 70 ha.

Thus, a threshold scale of around 100 ha appears to separate the catchments into two categories:

In the first category, larger than 100 ha, the correlation coefficient is above 0.6 and increases slowly with the area: empirical relations based on hydrological data allow the prediction of the variation in nitrates concentrations with a precision that increases with the area; this catchment scale is representative of the global functioning of the catchment of the region concerned.

In the second category, smaller than 100 ha, the correlation coefficient quickly becomes low when the catchment areas decrease: the same hydrological parameter is inadequate for predicting the nitrates content. Catchments of this category cannot be considered as representative of the region in question.

In other words, below a scale threshold, it becomes necessary to study local processes and their deterministic modelling, whereas above the defined scale threshold, empirical relationships exist, that are representative of the main processes of the catchments and can be used in global modelling. These conclusions are similar to the results of Wood *et al.* (1990, 1988), who defined a 100-ha Representative Elementary Area from a hydrological point of view. The concept of representative elementary area, first introduced using only topographic and pluviometric variabilities, can therefore be applied to define the relevant scale for geochemical studies of actual catchments.

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12. Characterisation of quick and slow streamflow components by unit hydrographs for single- and multi-basin studies

I.G. Littlewood & A.J. Jakeman

ABSTRACT

A method for identifying unit hydrographs for total streamflow (and often the 'quick' and 'slow' flow components thereof) is demonstrated for catchments of different size ($0.1\ km^2 < A < 10000\ km^2$) and data time interval (hours, days and months). Several possible applications of the technique for single- and multi-basin studies are discussed. A new 'low flows' catchment response statistic, the Slow Flow Index (SFI), is introduced and compared to the well known Base Flow Index (BFI).

INTRODUCTION

A key element in investigations of catchment systems is often the derivation of unit hydrographs from rainfall and streamflow records. The range of applications is considerable. For example, the objective might be to establish whether the unit hydrograph for a given location varies in shape or magnitude (or both) over time and, if so, to ascertain whether such changes are related to any physical changes in the catchment (e.g. land-use changes due to urbanisation, afforestation, deforestation, etc.). Or the objective might be to derive unit hydrographs for many basins and then to seek statistical, or more physically-based, relationships between, on the one hand, unit hydrograph shape and magnitude (UH parameters) and, on the other, physical catchment descriptors (PCDs) such as basin size, slope, drainage density, soil type, vegetation, etc. Given efficiently parameterised unit hydrographs and sufficiently good relationships between UH parameters and PCDs, it would then be possible to provide reasonable estimates of hydrographs at ungauged (flow) sites from rainfall records. A further use of unit hydrographs, currently receiving attention, is in assisting with assessment of the likely impacts of possible climate changes on different river flow regimes; a given climate change affecting a region might result in a spectrum of impacts at different points on the stream network in that region. Unit hydrograph models derived from rainfall and temperature records, which have parameters independent of climate sequence over the model calibration period, can be operated in simulation mode employing whatever rainfall and temperature input time series are deemed appropriate.

Few unit hydrograph models in the literature appear to be suitable for characterising long sequences of hydrological behaviour and for wide ranges of catchment type and data time interval. Furthermore, any flow components they prescribe are usually qualitative and not amenable to good definition numerically. For example, common steps are to make an intuitively reasonable (but fairly arbitrary) subtraction of 'baseflow' from streamflow, and to apply a simple 'losses' model to rainfall, prior to identification of a unit hydrograph for 'direct flow'; the analysis is often made on specially selected runoff events. In such models the unquestionable utility of the unit hydrograph approach is restricted, therefore, to dealing with just one, descriptively defined, streamflow component (direct flow). The other component (baseflow), i.e. that which is not direct flow, is likewise defined only qualitatively.

The purposes of this paper are to outline a methodology for identifying a unit hydrograph for total streamflow, where this can often be resolved into numerically well defined components, and to demonstrate and discuss its usefulness for a range of applications; rather than specially selected events the technique uses time series which contain many events. Full details of the methodology are given elsewhere (Jakeman *et al.*, 1990). When two components of the unit hydrograph are identified by the methodology they are, for convenience, referred to as 'quick' and 'slow' unit hydrographs. The 'quick' and 'slow' labels arise naturally from characteristic time constants calculable from the decay parameter of each component unit hydrograph. Furthermore, quick and slow components of streamflow can be estimated by applying the separate unit hydrographs to any sequence of rainfall adjusted for 'losses'. Thus it is possible to separate hydrographs into physically meaningful components (in the time domain at least - there are still problems and unanswered questions regarding the provenance of these flow components, as discussed by Littlewood & Jakeman, 1991).

The emphasis here is on demonstrating the technique. This is accomplished using a PC package known as IHACRES - Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data - (Jakeman *et al.*, 1991). The paper begins with a brief description of the model. This is followed by examples which illustrate its applicability across different catchment sizes (varying by orders of magnitude), hydroclimatology and data time interval (ranging from hours to months). Concluding remarks are made in a final section.

THE MODEL

The model used in IHACRES is based on unit hydrograph theory (e.g. Chow, 1964) which describes the variation of streamflow, x(t), over time t as a linear convolution between rainfall excess, u(t), and the unit hydrograph, h(t), viz.

$$x(t) = \int_0^t h(t-s)\ u(s)\ ds \tag{1}$$

Rainfall excess is the amount of rainfall which contributes to streamflow after 'losses' due to evapotranspiration have been deducted. When dealing with a continuous time representation, as in (1), the unit hydrograph is the streamflow response to a unit of rainfall excess applied instantaneously. When a discretisation of (1) is used, as in IHACRES, the corresponding input is unit rainfall excess over one sampling interval.

The assumptions of unit hydrograph theory are well known, but are conveniently summarised by Jakeman *et al.*, 1990. The methodology in IHACRES invokes an approximation of the unit hydrograph as a combination of exponential decays. Another interpretation of this is that rainfall excess is input to a system of linear reservoirs or storages from which there is an output which represents streamflow. The configuration may involve storages that are in parallel, in series or both. User-interaction with IHACRES can identify the most appropriate configuration in each case (see Jakeman *et al.*, 1990); the most common configuration encountered by the authors is two storages in parallel. More complex configurations tend not to give improved streamflow fitting capability compared to parallel storage configurations, and lead to parameter variances orders of magnitude larger (Jakeman & Hornberger, 1992). When derived in discrete-time, and in the case of two storages acting in parallel, the relationship between rainfall excess, u_k, and streamflow, x_k, at time step k can be written as a second-order transfer function of the form given by (2).

$$\left.\begin{aligned} x_k &= x_k^q + x_k^s \\ x_k^q &= \beta_q\, u_k - \alpha_q\, x_{k-1}^q \\ x_k^s &= \beta_s\, u_k - \alpha_s\, x_{k-1}^s \end{aligned}\right\} \qquad (2)$$

The parameters and streamflow component variables of the storage with the quicker throughput are designated with sub- or superscript q, and the slower storage properties are denoted with an s. The model is shown schematically in Figure 1. Alternatively, each storage can be defined by any two of the following three parameters which can be considered to be characteristic catchment properties; a time constant (τ), a relative throughput volume (V) and the contribution to the peak of the unit hydrograph (I). These characteristic catchment properties are defined as:

$$\left.\begin{aligned} \tau_{q\ or\ s} &= -\Delta/\ln(-\alpha_{q\ or\ s}) \\ V_{q\ or\ s} &= \beta_{q\ or\ s}/\{(1+\alpha_{q\ or\ s})g\} \\ I_{q\ or\ s} &= \beta_{q\ or\ s}/p \\ g &= \beta_q/(1+\alpha_q) + \beta_s/(1+\alpha_s) \\ p &= \beta_q + \beta_s \\ &\text{where } \Delta \text{ is the sampling time interval} \end{aligned}\right\} \qquad (3)$$

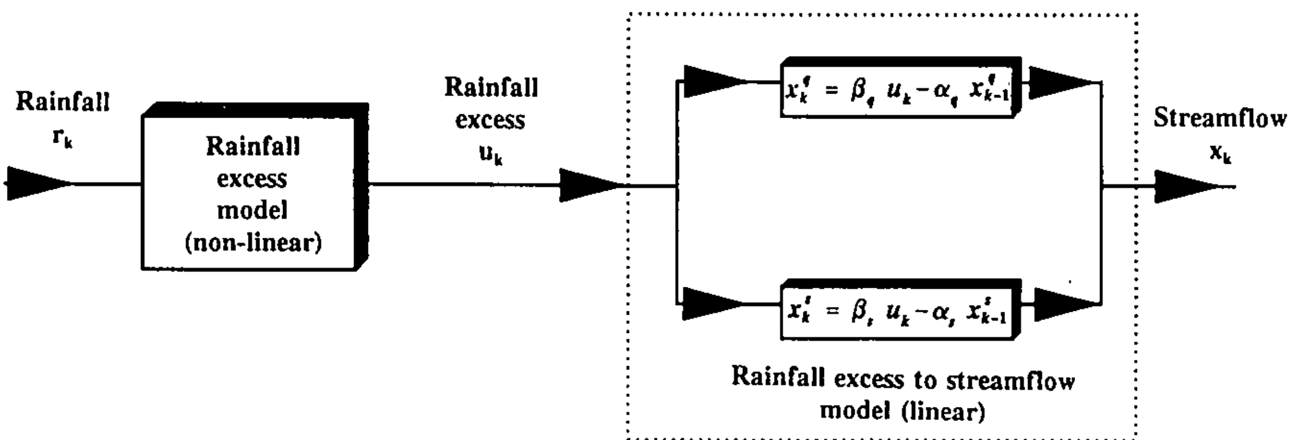

Figure 1 *Model structure: quick and slow flow components in parallel*

The package also allows use of a non-linear model of the relationship between rainfall and rainfall excess. Rainfall excess is highly dependent on the level of antecedent rainfall and may also depend on changes in evapotranspiration. The approach adopted in IHACRES is to account for variations in catchment wetness (i.e. the 'ripeness' of the catchment to produce streamflow at the time of the causative rainfall) by maintaining a running index of exponentially weighted past rainfall. A single optimal parameter which determines the length of 'memory' for exponentially weighting the past rainfall can be determined fairly rapidly by user-interaction with IHACRES. When modelling with daily data over long periods during which there may be seasonal changes in evapotranspiration, the rainfall, r_k, can be adjusted first according to the difference between the mean air temperature for the month and an overall maximum temperature determined by trial and error.

Thus

$$r_k^* = \left[1 - \frac{t_k}{t_m}\right] r_k \tag{4}$$

where t_m is a reference temperature greater than the recorded maximum for the location in question and, for calculating r_k^* in any given month, t_k is the observed mean temperature for that month.

A catchment wetness index, s_k, is calculated according to

$$s_k = s_{k-1} + \tau_w^{-1} \left(r_k^* - s_{k-1}\right) \tag{5}$$

where τ_w is the constant which determines the length of 'memory' for exponentially weighting past rainfall.

Rainfall excess is calculated by multiplying r_k^* by s_k at each time step and then scaling to ensure equality between volumes of rainfall excess and streamflow over the calibration period. Thus effective rainfall, u_k, is given by

$$u_k = const.\ r_k^*\ s_k \tag{6}$$

where const. is the scaling factor.

Jakeman and Hornberger (1992) have applied a temperature modification to the catchment wetness index instead of the rainfall. This is more appropriate when the catchment of interest is subjected to prolonged periods without rainfall.

EXAMPLES

Nant y Gronwen (CI6)

IHACRES has been developed, tested and applied over a wide range of catchment sizes using data intervals from hourly to monthly as appropriate. Initial development (Jakeman *et al.*, 1990) employed hourly data for two small (0.3 km^2 and 0.7 km^2) moorland catchments near

Llyn Brianne, in central Wales. These catchments are underlain by largely impermeable Ordovician shales, grits and mudstones and receive, on average, an annual rainfall of about 1800 mm. Figure 2 shows the IHACRES model-fit over a 17-day period in September 1987 for the larger of the two catchments (Nant y Gronwen at CI6). Nearly 95% of the initial variance in streamflow is accounted for by the model. In this case it appeared to be unnecessary to take into account any changes in evapotranspiration over the model calibration period; in (5) r_k^* was set to r_k, and the optimal value of τ_w was 86 hours. Figure 3 shows the rainfall, r_k, and the 'catchment wetness', s_k, and Figure 4 shows the resultant rainfall excess, u_k. The unit hydrographs are shown in Figure 5, and the corresponding separation of the hydrograph into its quick and slow flow components in Figure 6. The time constants, τ_q and τ_s, are 4.4 hours and 90 hours respectively. The relative throughput volumes, V_q and V_s, are about 0.4 and 0.6 respectively, and the relative contributions to the peak of the unit hydrograph for total streamflow, I_q and I_s, are about 0.92 and 0.08 respectively.

Teifi at Glan Teifi

The same methodology can give good results for many much larger catchments, e.g. those gauged by national hydrometric networks, but it is usually necessary to take into account any seasonal variations in evapotranspiration. The streamflow data for such catchments in the UK Surface Water Archive at the Institute of Hydrology are held as daily mean values. Figure 7 shows the IHACRES model-fit for the Teifi at Glan Teifi (894 km^2), in south Wales, over about three years' data from 25 July 1982 taken from the Surface Water Archive. The corresponding daily catchment rainfall was calculated by the 'triangle method' (Jones, 1983) on the basis of between 13 and 17 raingauges in and around the basin (depending on their different lengths of record, and any gaps). Mean monthly temperature representative of a 40 km by 40 km area (Meterological Office, 1982) which overlaps the catchment were employed in (4) to adjust the rainfall for seasonal variation in evapotranspiration. Selected model parameters, and characteristic catchment properties, were as follows.

τ_w	= 15 days	V_q	= .67
t_m	= 40 °C	V_s	= .33
τ_q	= 2.7 days	I_q	= .97
τ_s	= 51 days	I_s	= .03

Figure 8 shows the corresponding hydrograph separation; the slow flow component is reassuringly similar in shape to baseflow according to the well-known and intuitively reasonable BaseFlow Index (BFI) method (Institute of Hydrology, 1980). An analogous statistic to BFI, the Slow Flow Index (SFI), is given by V_s in (3). Whereas BFI for the Teifi at Glan Teifi is 0.53 (NERC, 1988) its SFI (V_s) is 0.33. This difference raises an interesting question. Which statistic is more indicative of the volumetric contribution to streamflow at Glan Teifi from relatively deep storage in the catchment? It is evident from inspection of the recorded hydrograph in Figure 7 that Teifi streamflow is highly seasonal. This is due largely to persistence of hydrologically effective rainfall over winter months and not to groundwater (the underlying geology is essentially impermeable and the annual average rainfall is greater than 1300 mm, usually with 60% or more falling in the winter months when evapotranspiration is low). The relatively high BFI could be due to this persistence of hydrologically effective rainfall. SFI is arguably the superior statistic for characterising the catchment hydrologically since it depends on a portioned response of the basin to a unit input of rainfall excess. BFI, on the other hand, is derived solely from the geometric shape of the hydrograph and is, therefore, only a flow statistic. Further work to compare SFIs and BFIs is planned.

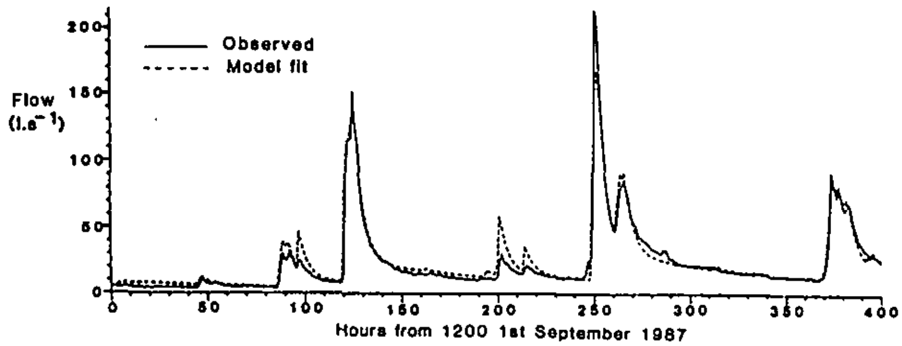

Figure 2 *Calibration model-fit for Nant y Gronwen at C16 (1-17 September 1987)*

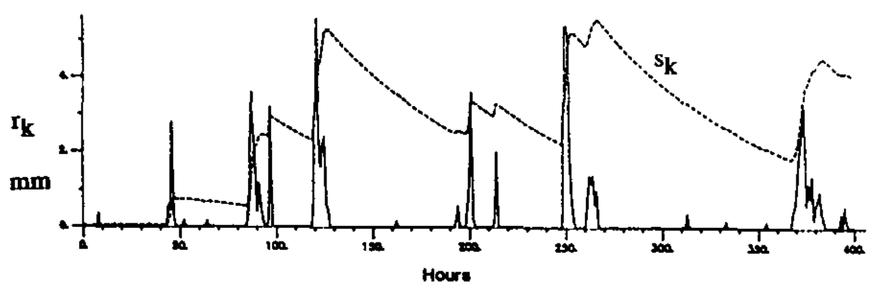

Figure 3 *Nant y Gronwen at C16 showing rainfall (r_k) and catchment wetness (S_k) for 1-17 September 1987*

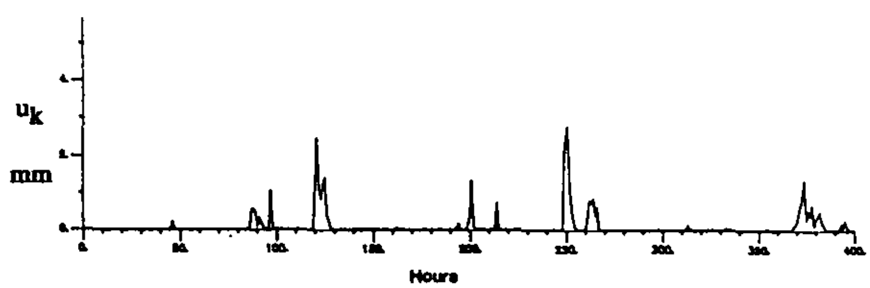

Figure 4 *Nant y Gronwen at C16, rainfall excess (u_k) for 1-17 September 1987*

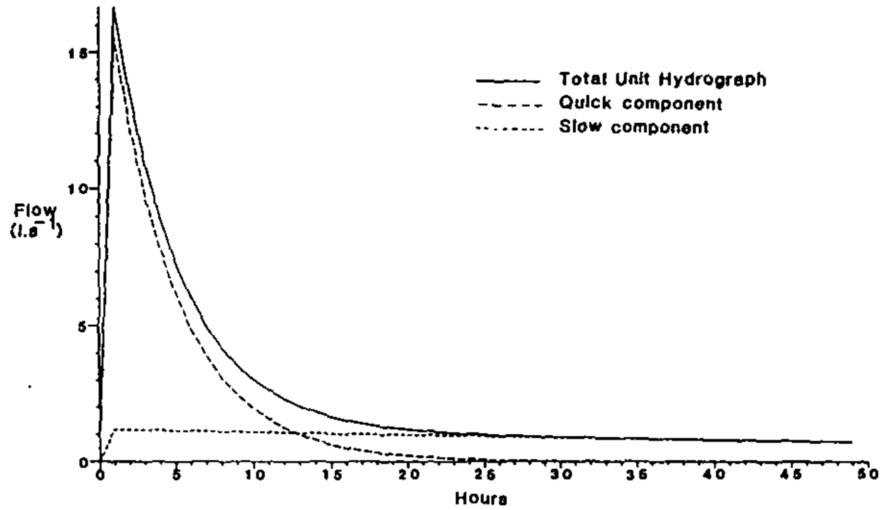

Figure 5 *Nant y Gronwen at C16 unit hydrographs*

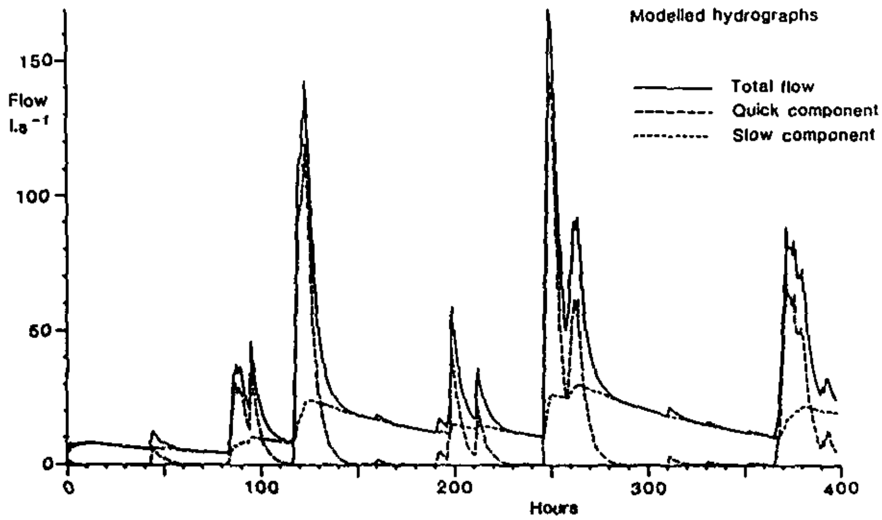

Figure 6 *Nant y Gronwen at C16, hydrograph separation for 1-17 September 1987*

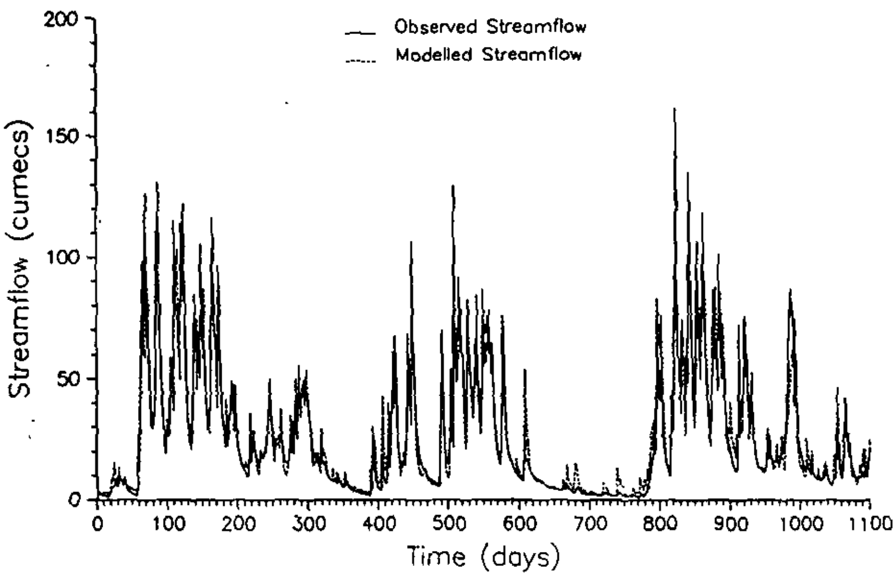

Figure 7 *Calibration model-fit for River Teifi at Glan Teifi, from 25 July 1982*

Exe at Thorverton

The utility of a rainfall - streamflow model depends largely on its ability to simulate streamflow over a period of record not used for its calibration. Figure 9 shows the calibration model-fit over about three years' daily data from 29 June 1961 for the Exe at Thorverton (601 km^2), southwest England. (The rainfall, streamflow and temperature data were obtained and prepared as described for the Teifi example.) Despite some sequences within this period where the model-fit is not as good as it might be (particularly at about time step 555) the model accounts for over 80% of the initial variance in streamflow. (Time step 555 in Figure 9 corresponds to early January 1963 when the catchment response was probably affected by snow.) Figure 10 shows the result of applying the same model in simulation mode to a period some 24 years later, i.e. for about three years from 3 June 1985. It is evident from Figures 9 and 10 that the essential dynamic hydrological behaviour of the catchment described by the model calibrated on data from the 1960s is still valid in the 1980s. Selected model parameters and characteristic catchment properties were as follows:

τ_w	= 10 days	V_q	= .67
t_m	= 25 °C	V_s	= .33
τ_q	= 3.1 days	I_q	= .97
τ_s	= 53 days	I_s	= .03

It is interesting that the SFI (V_s) for the Exe at Thorverton is, at 0.33, the same as for the Teifi at Glan Teifi. The BFI at Thorverton (NERC, 1988) is 0.51 (cf. 0.53 at Glan Teifi). The rainfall regime for the Thorverton catchment is similar to that for Glan Teifi (about 60% of the 1269 mm annual average rainfall usually occurs in the winter months) and therefore a similar argument can be made to explain the relatively high BFI.

Thames at Kingston

The previous examples demonstrate IHACRES for selected catchments at either end of a range in size covering three orders of magnitude. Other examples (not given here) indicate the applicability of IHACRES to many catchments with areas between these limits. Depending on the flashiness of response to rainfall it appears that small catchments (e.g. less than 1 km^2) typically require hourly data to estimate quick and slow flow components. Jakeman & Hornberger (1992) use 6-minute data for a detailed analysis of a 490 m^2 experimental hydrological system created near Nanjing, China. Quick and slow flow components can be quantified from daily data for many catchments ranging in size from about 10 km^2 to 1000 km^2. When a catchment of a further order of magnitude in size was investigated it was found that a good model-fit was obtained using monthly data, but that only one component of flow could be identified reliably. Figure 11 shows the IHACRES calibration model-fit using monthly 'naturalised' streamflow data (i.e. adjusted for major abstractions and discharges) for the Thames at Kingston (9948 km^2) from August 1953 to September 1989, where (2) was replaced by (7). The model accounts for 84% of the initial variance in streamflow and the model parameters were as follows:

$$x_k = \beta u_k - \alpha x_{k-1} \tag{7}$$

τ_w = 6 months
t_m = 21 °C
α = .4702 (τ = 1.3 months)
β = 1.9876

The rainfall and flow data employed were calendar month values from the Surface Water Archive, and the temperature data were from a monthly series representative of Central England starting in 1659 based on work by Manley (1974). The streamflow record for the Thames at Kingston (or nearby) begins in 1883. Although, strictly, the calendar month data violate a modelling requirement for periodic data the model accounts for about 84% of the initial variance in flow. Despite some indication of systematic underestimation of annual minima the model performs fairly well during, and immediately after, the 1976 Drought (i.e. between months 250 and 300 in Figure 11).

Figure 12 shows the same model applied in simulation mode over the period August 1884 to April 1951; Figure 13 is an expansion of Figure 12 between months 600 and 800 (August 1934 to April 1951). There are discrepancies between the recorded and modelled monthly flows, as might be expected with any model, but these are relatively minor. It appears, therefore, that the model calibrated using data from 1953 to 1989 captures the essence of a monthly flow regime which has been sensibly invariant over the whole period of record. This preliminary result indicates that any effects of changes within the catchment since the 1880s in land-use and water supply practice are not detectable in the monthly naturalised flow record. Leakage at the measuring weir prior to 1951 (NERC, 1986) may affect annual natural streamflow minima in the record but the effect on the overall monthly flow regime is not significant. Furthermore, the adjustments made to gauged monthly flows at Kingston, which have had to include allowances for an increase in abstractions for water supply from about 4 m^3s^{-1} in 1883 to about 20 m^3s^{-1} in 1980 (NERC, 1986), appear generally to have been made consistently. The analysis, therefore, endorses the integrity of the Kingston monthly naturalised streamflow record in the Surface Water Archive; this form of data quality control can be applied to archived catchment rainfall and streamflow records generally. It should be noted, however, that a more detailed analysis of the Kingston record, using daily or weekly data, might detect anthropogenic changes in the Kingston flow regime and the effects on low flows of leakage at the measuring weir prior to 1951.

Concluding remarks

The IHACRES methodology has been (and continues to be) developed with characterisation and comparison of catchments uppermost in mind. Good model-fits have been obtained for a wide range of catchment types and sampling time intervals. The ability, in many cases, to separate hydrographs into quick and slow flow responses from information solely in records of rainfall, streamflow and, when appropriate, temperature data make IHACRES a potentially useful analytical tool for many applications. The technique has been applied to compare the hydrological responses of a pair of catchments near Balquhidder, Scotland (Jakeman *et al.*, in press), attempting to detect the effects of afforestation in one and clear-felling in the other. It has also been applied to pairs of catchments elsewhere: in Wales (Jakeman *et al.*, 1990); and in the Australian Capital Territory and the United States of America (Jakeman & Hornberger, 1992). The detailed nature of the quick and slow flow hydrological responses of a very small experimental plot near Nanjing, China has also been investigated using IHACRES (Jakeman & Hornberger, 1992). Littlewood and Jakeman (1991) used IHACRES to assist with an examination of claims in the literature, based on isotope and chemical tracer studies, that large fractions of peak flows in some catchments can comprise 'old' water, i.e. water already in the catchment prior to rainfall.

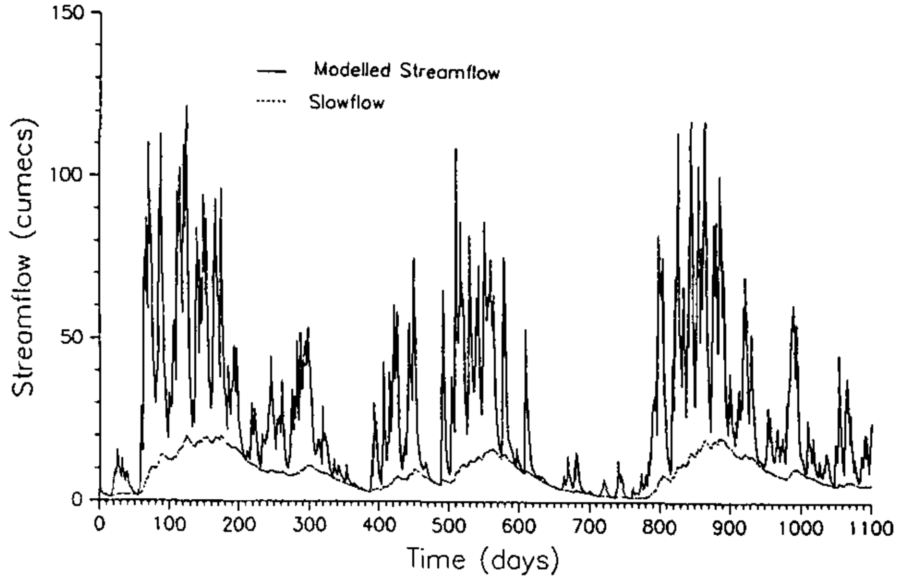

Figure 8 *Teifi at Glan Teifi hydrograph separation from 25 July 1982*

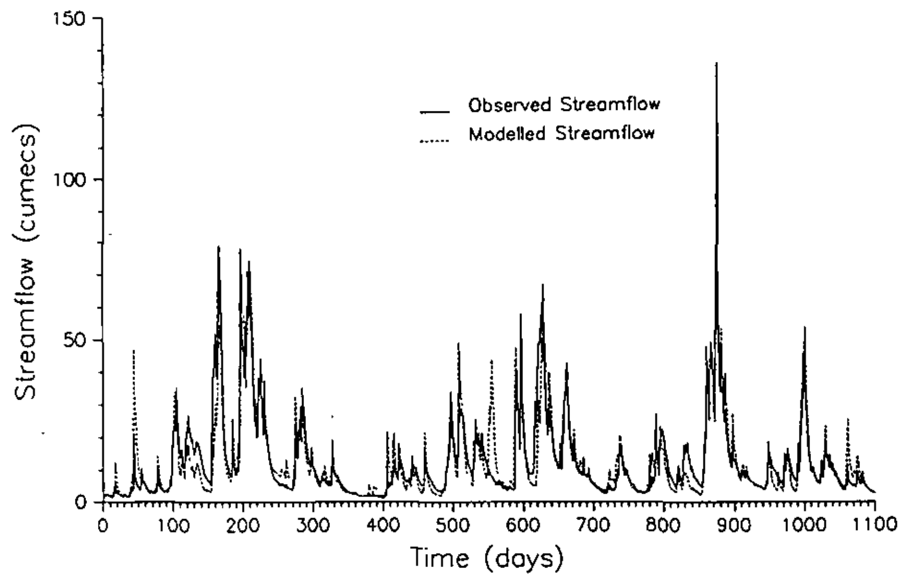

Figure 9 *Calibration model fit for River Exe at Thorveton from 29 July 1961*

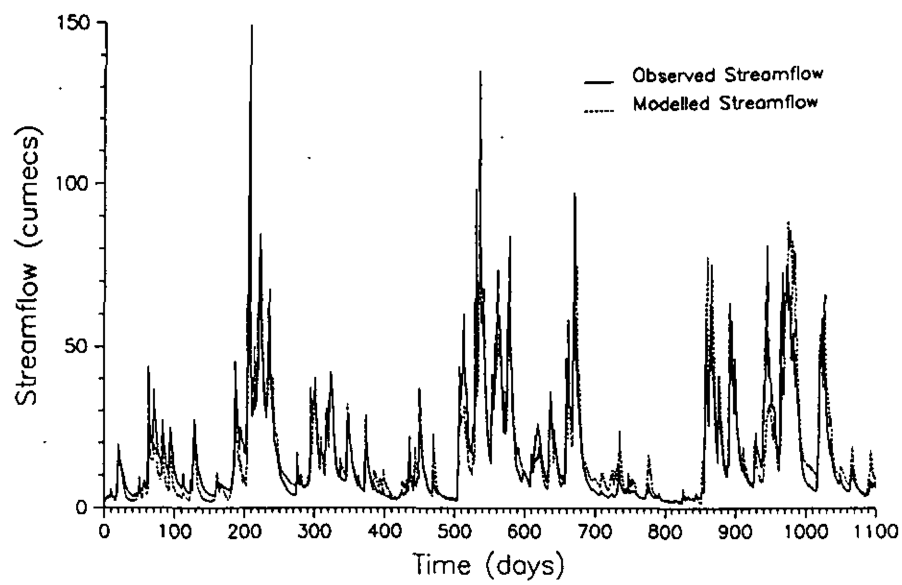

Figure 10 *Simulation model-fit for Exe at Thorveton from 3 June 1985*

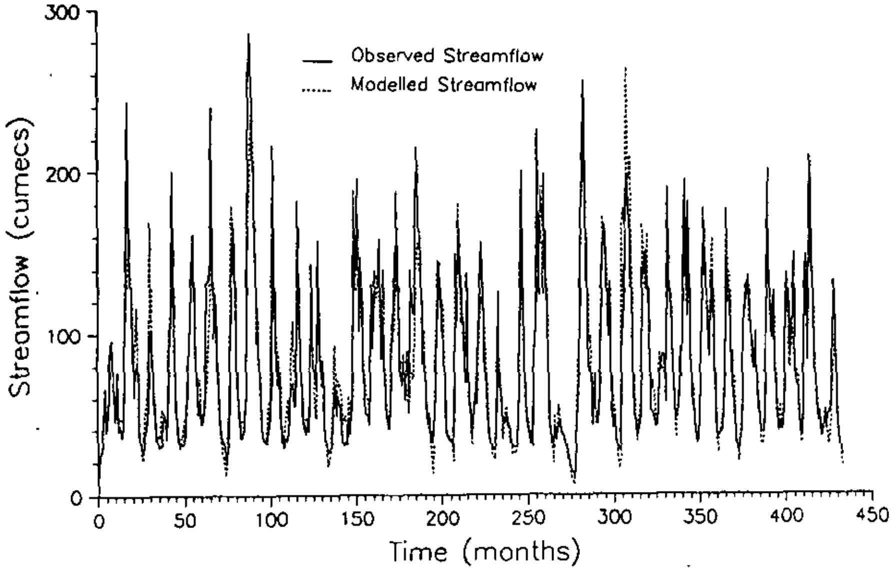

Figure 11 *Calibration model-fit for River Thames at Kingston, August 1953 - September 1989*

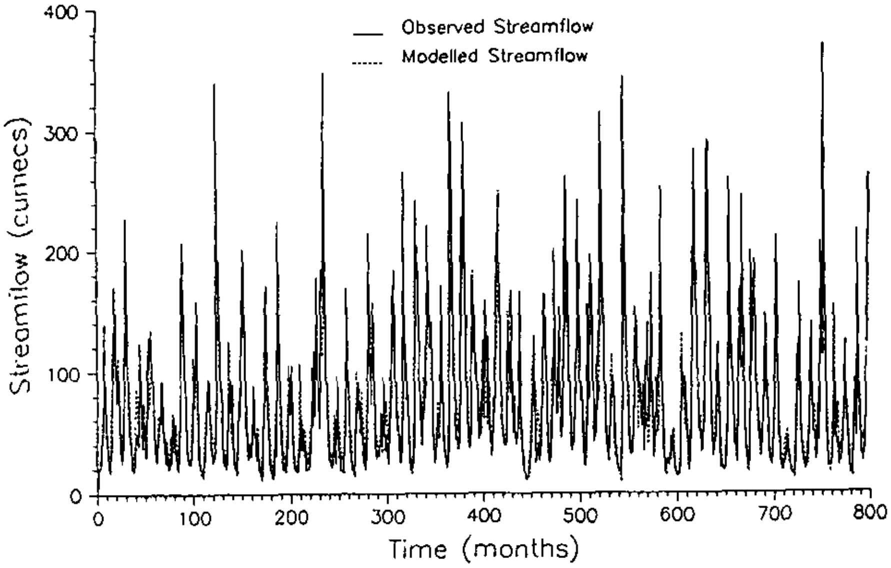

Figure 12 *Simulation model-fit for Thames at Kingston, August 1884 - April 1951*

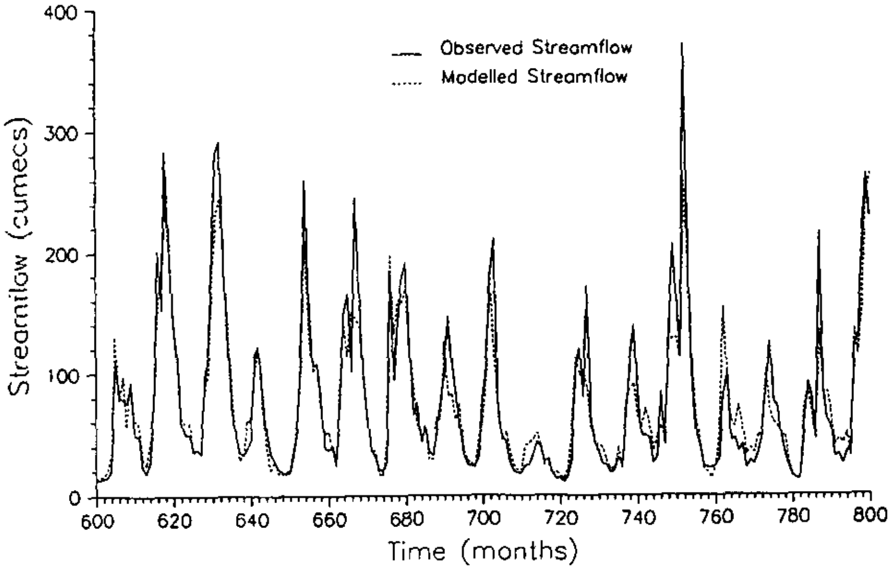

Figure 13 *Simulation model-fit for Thames at Kingston, August 1934 - April 1951*

The additional examples given in this paper (and many others not given here) have arisen during the planning stages of work aimed at linking, dynamically, climate variables (principally rainfall and temperature), physical catchment descriptors (PCDs) and characteristic catchment properties (Jakeman *et al.*, 1992). While IHACRES, as described in this paper, performs well on a wide range of catchment types, improvements and enhancements to the methodology are planned. Future work will include tests of alternative 'losses' sub-models to improve upon (4) to (6); recent trials using a temperature-dependent τ_w in (5) have given encouraging results. Attention will also be given to the utilisation of information in water quality and well level records (the latter to widen the range of catchment types amenable to analysis by IHACRES to include those dominated by groundwater).

IHACRES has been shown to be a potentially valuable addition to the suite of analytical techniques available for obtaining information (e.g. characteristic time constants, a Slow Flow Index and relative contributions of quick and slow flow to unit hydrograph peaks) from experimental basin databases and from the UK Surface Water Archive. Potential applications of interest currently are derivation of a regionalised hydrological model within a GIS framework, and assessment of scenario climate change impacts on hydrological response at a range of catchment scales. The authors would be pleased to hear of other potential applications of the IHACRES methodology. A PC version of IHACRES is being developed jointly by the Institute of Hydrology and the Centre for Resource and Environmental Studies, Canberra, and it is intended this will become available commercially.

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13. Comparison of basin hydrological characteristics using only one lumped parameter: preliminary note

A.M. De Felice, W. Dragoni & G. Giglio

ABSTRACT

A simple conceptual model was used to classify basins in a concise manner. The model, comprising two tanks, computes the mean monthly streamflow from the mean monthly rainfalls and temperatures in an average year. The first tank represents soil and vegetation and governs the rainfall-evapotranspiration relationship according to the Thornthwaite-Mather method. The second reservoir, fed by the first, is linear and is defined by a single parameter, β and controls the monthly yield of the available water. Application of the model to nine basins indicates that β is strongly linked to the overall permeabilities of the rock formations outcropping in the area, and is rather independent of the catchment size. For high permeability basins the value of β is around 0.5, and for low permeability it is around 0.1 or less.

INTRODUCTION

A simple conceptual model has been set up in order to find parameters enabling a simple and efficacious comparison of the way in which basins of different areas and lithologies release the available water. The model simulates the mean monthly flow of streams, given mean monthly rainfalls and temperatures in an average year.

DESCRIPTION OF THE MODEL

The model is a variation of the well-known Thornthwaite-Mather method for the hydrologic balance of a system (Thornthwaite-Mather, 1957). It represents the basin as two reservoirs in series: the first represents the soil and governs the rainfall - evapotranspiration relationship, while the second reservoir, fed by the first, takes on the "invariant characteristics" of the basin, and controls the monthly yield of the available water. Here the term "invariant characteristics" refers to the set of characteristics of the basin which controls the monthly yield and which is independent from the climate, season, vegetation or anything else that can change over a short time. Thus, it is reasonable to assume that the term "invariant characteristics" is synonymous with the geological and morphological characteristics, and, at least partially, the soil thickness.

The second reservoir of the model is linear and characterized by a dimensionless coefficient β. Thus we have:

$$q_{(i)} = \beta(W_{(i-1)} + C * S_{(i)}) \qquad (1)$$

$$W_{(i)} = (1 - \beta)\,(W_{(i-1)} + C * S_{(i)}) \qquad (2)$$

where:

$q_{(i)}$	=	computed basin yield during month (i), (mm/month);
$W_{(i)}$, $W_{(i-1)}$	=	reserves available in the second tank in months (i) and (i-1), (mm/month); the model imposes $W_{(0)} = W_{(12)}$;
$S_{(i)}$	=	water surplus in month (i), (mm/month);
C	=	exchange coefficient (dimensionless).

The coefficient C was introduced in the model since the estimation of actual evapotranspiration (based on temperature readings alone) is always poorly approximated and - especially for small basins in areas with highly permeable rocks - underground exchanges with adjacent systems often may not be negligible. The coefficient C is assumed to be constant for all months, and, during calibration, it always makes the computed total annual yield, produced by the basin, coincide with the measured flow. Thus we have:

$$\sum_{i=1}^{i=12} Q_{(i)} = \sum_{i=1}^{i=12} \beta\,(W_{(i-1)} + C * S_{(i)}) = \sum_{i=1}^{i=12} F_{(i)} \qquad (3)$$

where:

$Q_{(i)}$, $F_{(i)}$ = computed and measured flow during month (i), (mm/month).

It is necessary to emphasize that C is not a coefficient whose main task is to compensate for errors in computing evapotranspiration, but rather the underground flow between neighbouring basins. The importance of this flow is supported by the data of Table 1, taken from an official publication (Min. LL.PP., 1963) and Tonini, 1959. Although some of Tonini's data have been questioned (Villi, personal communication, 1992) on the whole Table 1 shows how the overall underground exchanges between neighbouring basins, up to several thousand square kilometres in size, can be quite important and much greater than any reasonable error in estimating evapotranspiration, rainfall or streamflow.

According to Thornthwaite-Mather, $\beta = 0.5$ for "large" basins, while it is greater for watersheds measuring a "few square kilometres". In our model β is not fixed "a priori".

In the model the water-holding capacity of the soil basin is fixed according to the Thornthwaite-Mather criteria, and the actual evapotranspiration is computed according to the same criteria. The model is calibrated by assigning values to coefficients C and β which minimize the mean square deviation between measured and computed monthly flows.

Table 1 *Average Yearly Runoff Coefficient of some Italian Basins (Min. LL. PP., 1963)*

Basin (gauging station) and observation period	Area	Average yearly Rainfall	Average yearly Flow	Average yearly Runoff coefficient
	km²	mm	mm	C_d
PETTORINA[1] (Malga Ciapela) 1941-50	28	1048	1105	1.05
BRENTA[1] (Sarson-Bassano) 1922-50	1567	1386	1433	1.03
ADIGE[1] (Tel) 1927-49	1675	649	656	1.01
RUTOR[1] (Promise) 1931-5	50	1414	1743	1.23
NERA[2] (Visso)1928-29, 1931-43	59.7	1051	1672	1.59
USSITA[2] (Visso) 1931-43	39.7	1159	1537	1.33

[1]Tonini, 1959; [2]Min.LL PP, 1963

It is necessary to emphasise that the purpose of the model used here is not to predict the monthly yield; rather it to classify basins according to the value of parameter β. Models with more parameters and different structures can be built or are available for a good continuous flow simulation (e.g. Linsley & *al.*, 1982; Singh, 1989; Thiery, 1990). However, up to now, their use in classifying catchment behaviour seems to be rather impractical.

Parameter C depends both on the physical characteristics of the considered basin and on those of the neighbour basins. Thus it seems that C is not as good as β for classifying a given basin.

DESCRIPTION OF THE BASINS STUDIED

Generalities

As a preliminary, the model was applied to nine basins, two with high permeability rocks, four with low permeability rocks and three with an intermediate permeability. All are hill or mountain basins in central Italy, with no months having an average temperature below the freezing point. The area of the basins varies from about 11 km² (Rio Acquina river) to 1956 km² (Chiascio river).

Table 2 Bulk permeability of some rocks (modified from Ground-water studies, UNESCO, 1977)

Rock Types	**Permeability range (cm/s)** High 10^{2}	High 10^{0}	Medium 10^{-2}	Medium 10^{-4}	Low 10^{-6}	Low 10^{-8}
Sediments, unconsolidated						
Gravel	═	═				
Coarse sand		═	═			
Medium to fine sand			═	═		
Silt					═	═
Clay, till						═
Sediments, consolidated (1)						
Limestone, dolomite	═	═	═	═	═	═
Coarse, medium sandstone		═	═			
Fine sandstone, argillite, flysch				═	═	═
Shale, siltstone					═	═
Volcanic rocks (1)						
Basalt	═	═	═	═	═	═
Acid volcanic rocks				═	═	═
Crystalline rocks (1)						
Plutonic and metamorphic				═	═	═

(1) Permeability increases with fracturing

In the following, the terms indicating the permeability refer to the overall characteristics of the rocks outcropping in the watersheds, and have the meaning given in Table 2. In the paragraphs below which specify the relevant characteristics of the basins, the geological description is kept to a minimum. Besides the references given for some individual basins, the interested reader can find a detailed geological description and a list of specific references in (AA.VV., 1982; Boni & *al.*, 1986). Except where otherwise stated hydrometeorologic data have been taken from publications of Ministero dei Lavori Pubblici - the Ministry of Public Works (Min. LL. PP., 1926 - 1980; 1963; 1966).

Low permeability basins

Rio Acquina River (gauging station: Carestello). Location: 43°17' N, 12°31' E. Area: 11 km^2. Average altitude : 652 m a.s. l.. Hydrometeorological Data: February 1985 - January 1989, (De Felice & Dragoni, 1991).
Geology: flysch, clays, argillites and fine sandstone. The main rock formation is the "Marnoso-arenacea", of the Lower-Middle Miocene.

Reno River (gauging station: Pracchia). Location: 44°03' N, 10°24' E. Area: 41 km^2. Average altitude : 890 m a.s. l.. Hydrometeorological Data: 1961 - 1970.
Geology: a) fine sandstones and marls (Tuscan Units, Cenozoic Flysch); b) calcareous marly sandstones and fine sandstones (Ligurian Units, Lower Cretaceous - Upper Eocene).

Farma River (gauging station: Ponte a Torniella). Location: 43°04' N, 11°07' E. Area: 70 km^2. Average altitude : 482 m a.s. l.. Hydrometeorological Data: 1961 - 1971, (Barazzuoli *et al.*,1986)
Geology: a) metamorphic basement (Palaeozoic and Triassic); b) evaporitic limestone ("Calcare cavernoso" formation, Middle-Upper Triassic); c) fine sandstones, argillites and shales (Units of Ligurian facies, from the Upper Jurassic to the Cretaceous); d) clays, sandy clays, conglomerates, sands (Miocene - Pleistocene); e) volcanic rocks (Lower Quaternary) and alluvium (Messinian). The "Calcare cavernoso" and the sands of group d) have high permeability, but they cover an area smaller then 10% of the total area of the watershed.

Tiber River (gauging station: S. Lucia). Location: 43°25' N, 12°16' E. Area: 934 km^2. Average altitude : 580 m a.s. l.. Hydrometeorological Data: 1929 -1935; 1937-1939.
Geology: a) flysch (Tuscan Units, Lower-Middle Miocene); (Umbria - Marches succession, formation "Marnoso Arenacea", Lower-Middle Miocene); b) fine sandstones, argillites, marly limestones (Ligurian Units, Monte Morello Units, Upper Cretaceous - Upper Eocene); c) low-medium permeability alluvium (Post - Villafranchian).

High permeability basins

Aniene River (gauging station: Subiaco). Location: 41°55' N, 13°06' E. Area: 233 km^2. Average altitude : 1109 m a.s. l.. Hydrometeorological Data: 1930 - 1939.
Geology: a) limestones and dolomites (Latium-Abruzzi succession, Upper Triassic-Upper Miocene); b) flysch (Umbria - Marches succession, Middle Miocene-Lower Pliocene); c) conglomerates (Quaternary). The flysch is present over a negligible percentage of the watershed; karst phenomena very common.

Nera River (gauging station: Torre Orsina). Location: 42°34' N, 12°45' E. Area: 1445 km^2. Average altitude : 1014 m a.s. l.. Hydrometeorological Data: 1926 - 1985, (Cencetti *et al.*, 1989).
Geology: a) limestone (formation of Calcare massiccio, Lower Lias); b) limestone, siliceous limestone, marly limestone, marls (Umbria - Marches succession, Middle Lias - Oligocene). The area covered by low permeability rock is very small, and fracturing is generally very high.

Medium permeability basins

Tordino River (gauging station: Teramo). Location: 42°39' N, 13°42' E. Area: 147 km^2.

Average altitude : 930 m a.s. l.. Hydrometeorological Data: 1947 - 1956.
Geology: flysch, with a large percentage of sandstones and conglomeratic sandstones (Umbria - Marches succession, Middle Miocene - Lower Pliocene).

Chienti River (gauging station: Pieve Torina). Location: 43°03′ N, 13°02′ E. Area: 118 km^2. Average altitude : 924 m a.s. l.. Hydrometeorological Data: 1939 -1940; 1948; 1953 -1959.
Geology: a) limestones, dolomites, marly - siliceous - nodular limestones (Upper Triassic - Lower Cretaceous); b) marly limestones and siliceous limestone (Lower Cretaceous - Lower Miocene). The rock formations of both group a) and b) belong to the Umbria-Marches succession.

Chiascio River (gauging station: Torgiano). Location: 43°02′ N, 12°26′ E. Area: 1956 km^2. Average altitude : 530 m a.s. l.. Hydrometeorological Data: 1930-1939.
Geology: a) limestones, dolomites, marly - siliceous - nodular limestones (Upper Triassic - Lower Cretaceous); b) marly limestones and siliceous limestone (Lower Cretaceous - Lower Miocene); c) marly limestone, marls (Lower Cretaceous - Lower Miocene); d) flysch (Marnoso - Arenacea formation, Lower- Middle Miocene); d) clays, inglobing limestones, sandstones and ophiolites (formation of the Argille Scagliose, Jurassic-Eocene); e) clays, sands and conglomerates (Pliocene); f) alluvium (Quaternary).The rock formations of groups a), b), c), d) belong to the Umbria-Marche succession.

MODEL APPLICATION

Results and discussion

Table 3 presents the results obtained by the application of the model, while Figure 1 shows an example, for each type of basin, of the measured and simulated flows. It is interesting to note that, as expected, the value of coefficient C shows the greatest difference from 1 for "high permeability" basins. This gives a confirmation of the validity of the basin classification according to the permeability.

Apart from the basin's dimensions and the value of C, parameter β takes on values around 0.5 for basins with low permeability rock. For highly permeable basins, on the other hand, β takes on values around 0.1. Figure 2 shows how the behaviour of a "low permeability" river can be transformed into that of a "high permeability" river by simply varying the coefficient β.

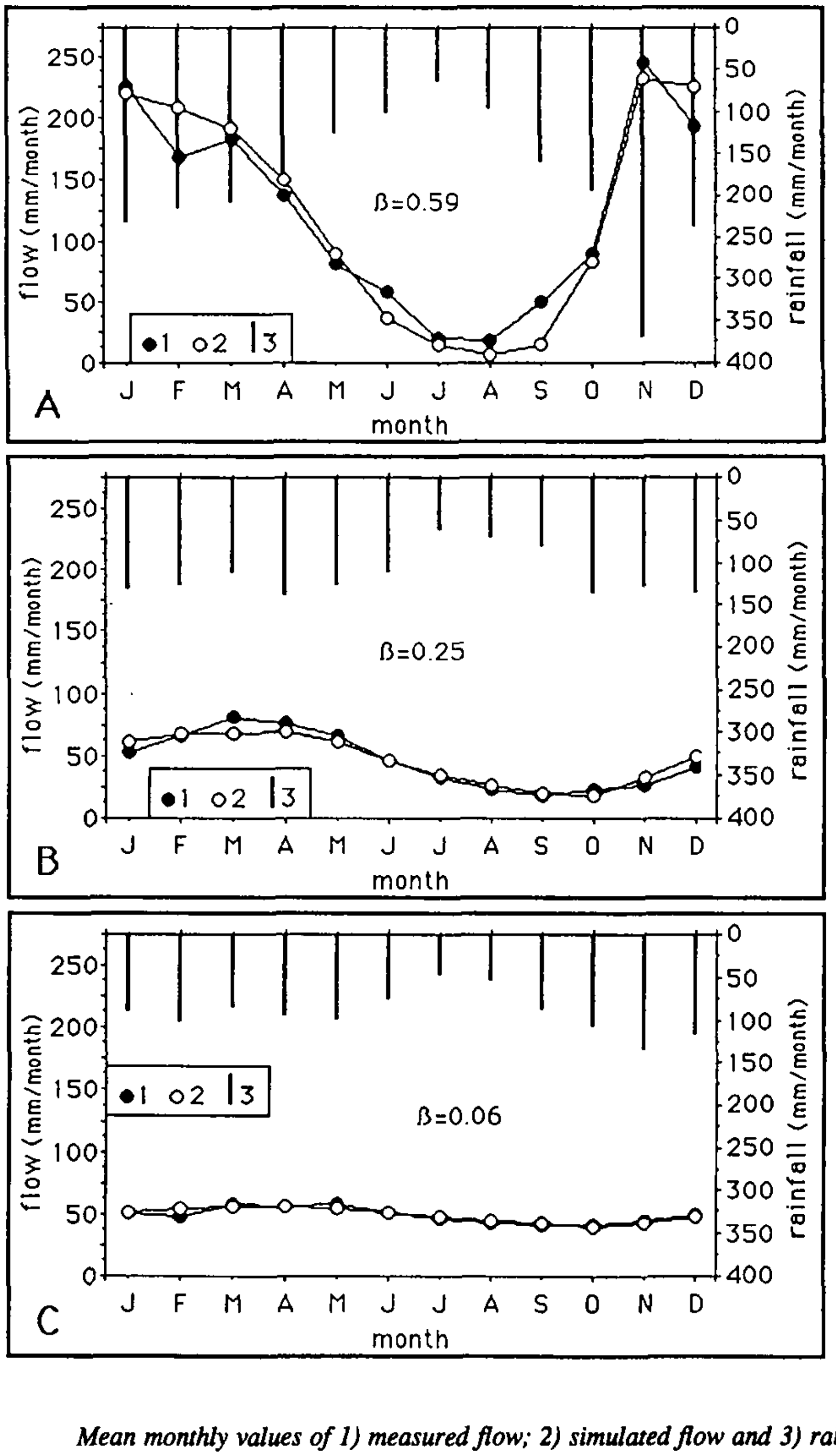

Figure 1 *Mean monthly values of 1) measured flow; 2) simulated flow and 3) rainfall for three catchments with different permeabilities: a) Reno (ß=0.59) b) Chienti (ß=0.25) and c) Nera (ß=0.06)*

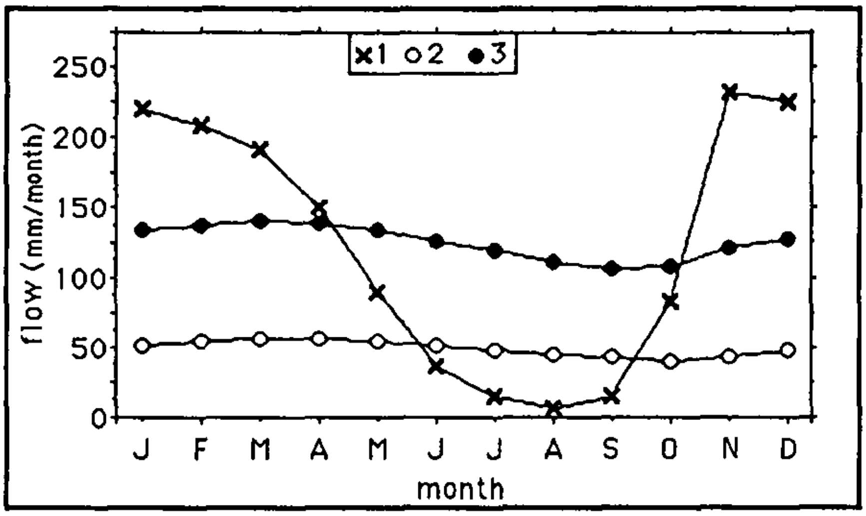

Figure 2 *Effect on simulated flow of the value of parameter β*
1) Reno (β=0.59, real value)
2) Nera (β=0.06, real value)
3) Reno (β=0.06)

Table 3 *Results of the model application - parameter values and model fit*

Basin	β	C	C_{Turc}	Std. Error (mm)
<u>Low permeability</u>				
Acquina	0.46	0.93	0.99	7.8
Reno	0.59	0.98	0.95	22.1
Parma	0.46	0.96	0.98	10.5
Tiber	0.47	0.95	0.96	15.2
<u>Medium permeability</u>				
Chienti	0.25	0.77	0.73	6.8
Tordino	0.21	1.10	1.02	13.9
Chiascio	0.37	0.77	0.79	11.0
<u>High permeability</u>				
Aniene	0.16	1.57	1.57	15.2
Nera	0.06	1.18	1.10	2.5

As an additional check on the way that the applied model computes the water surplus and on the meaning of C a new coefficient (C_{Turc}) was computed:

$$C_{Turc} = \frac{Q_y}{(P_y - AE_y)} \tag{4}$$

where Q_y = yearly average measured flow;
P_y = yearly average rainfall;
AE_y = yearly average actual evapotranspiration according to the Turc formula (Turc, 1954). On a yearly average basis, in the temperate zones, the Turc formula gives generally good results (Castany, 1968; Celico, 1988; De Felice & Dragoni, 1991).

Conceptually C_{Turc} has the same meaning as coefficient C in the model: for a given basin it gives an idea of the groundwater flow to or from neighbour watersheds. Table 3 shows that the model and the Turc method give similar values for any considered basin. It could seem that, in characterizing the monthly water release process of a given basin, the coefficient β could be substituted by other coefficients, such as the variation coefficient of the monthly flow, the coefficients of the regression lines between annual rainfalls and flows, or between flows in month (i) and precipitation in months (i), (i-1), (...), (i-n). However, since all these coefficients reflect climatic conditions as well as the "invariant" characteristics of the basin, we feel that β is the most suitable for concisely representing these characteristics.

CONCLUSIONS

The preliminary results presented here suggest the following considerations.

- Further work on a much larger number of basins is necessary for checking the validity of the approach presented. In any case further work is also necessary for defining more accurately the characteristics which determine parameter β. Perhaps the drainage density, or other simple to determine morphometric data, could help in estimating β in basins without hydrometric data.

- Parameter β should be independent of the climatic conditions: basins having the same morphological and geological characteristics should have the same β, aside from their geographical location.

- As expected, up to now, parameter C results in being very close to 1 for low permeability basins. However, the presumptive determining of parameter C, tied not only to the type of rocks in the basin, but also to its tectonic structure and to the errors of estimates of many climatic parameters, will always remain problematic.

- Evapotranspiration in the model is computed according to the Thornthwaite-Mather method; probably the results could be improved using more sophisticated methods.

- The model could be modified to be applied to a continuous set of data, i.e. not just average monthly data, but to a time series of monthly temperature, rainfall, flow. This would allow the introduction of one or two additional coefficients, still linked to the invariant characteristics of the watershed, to account, for instance, for the direct and delayed flow components.

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14. Hydrological and hydrochemical comparison of snow accumulation and melting in mountainous basins

G. Babiaková, D. Bodiš, & D. Palkovič

ABSTRACT

Hydrological and hydrochemical parameters are described and compared for two mountain basins. The study, over several winter seasons included acid deposition of SO_4^{2-} and NO_3^-, comparing their export from the two basins (as concentrations and as loads) and their overall annual balance. An integrated model was used to simulate both snowmelt quantity and quality from the seasonal snow cover.

INTRODUCTION

Recent studies suggest that acid precipitation is responsible for the progressive acidification of soils and water in Central Europe as well as in other areas, in particular Scandinavia and parts of North America. In mountain basins, where there is considerable snow accumulation during winter, the preferential release of solutes during snowmelt may produce short-term episodes of very acid stream water. Studies, providing information about episodic acidification in Canada, Europe and the United States are described and discussed by Wigington *et al.*, 1990.

Since 1985, the Institute of Hydrology and Hydraulics, Bratislava, has devoted attention to the problems of ion concentrations in snow cover and their fractionation during snowmelt. The first studies, in cooperation with the Dionýz Štúr Institute of Geology, Bratislava, dealt with SO_4^{2-}, NO_3^- and pH distributions in the winter season with regard to basin altitude, distribution of these ions in snow layers and preferential release of solutes during snowmelt (Babiaková & Bodiš, 1985, 1986).

The constructed "Integral Model of Snow Accumulation and Snowmelt Brystrianka" (IMAT) Babiaková *et al.* (1988, 1990), applied and verified in the Bystrianka basin, can be used for both the simulation and forecast of snow accumulation and the accumulated SO_4^{2-} washout. The model relates surface runoff acidity and precipitation acidity by quantifying the progressive hydrological and chemical input and output sequences of components representing physical entities (e.g. the soil horizons). In this paper two mountain basins (Bystrianka and Jalovec) are presented and compared. The following aspects were compared: concentration - discharge conditions, cumulative outflow, SO_4^{2-}, NO_3^- from basin and input - output balance. The utilization of an integrated model for the simulation of both snowmelt quantity and quality from seasonal snow cover is briefly described. Possibilities for applying the model to other basins are also discussed.

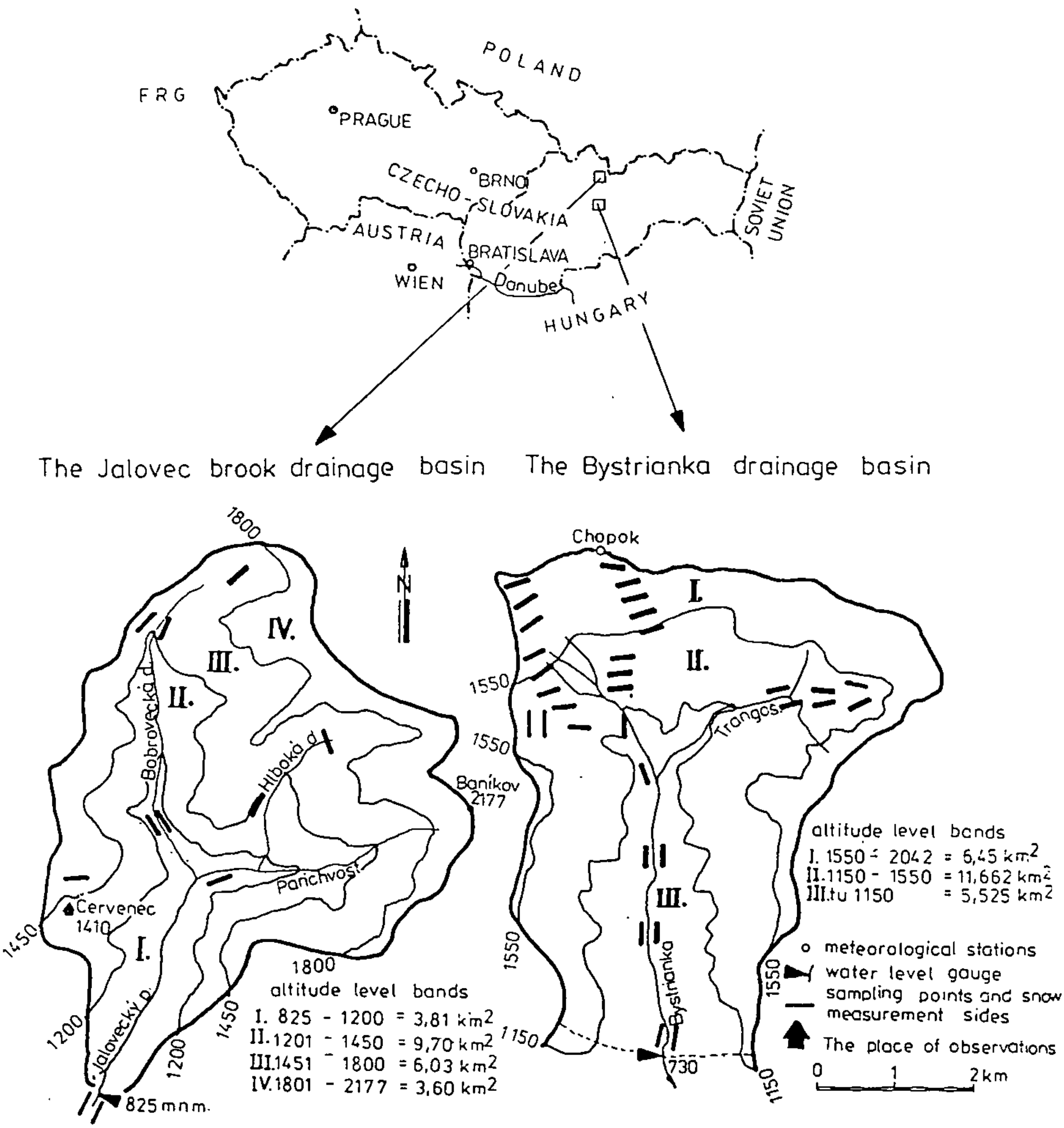

Figure 1 ***The Jalovec and Bystrianka basins***

BASINS

The basins modelled (Figure 1) are situated in the Tatrid crystalline massif composed of granitic and metamorphic rocks of the Bystrianka basin. The Jalovec brook catchment contains only granitic rocks. Within the Bystrianka region there is a narrow belt of lower and middle trias.

The Bystrianka basin is 23.15 km^2, and it is considered to be representative of snow accumulation under mountain conditions. Altitude ranges from 700-2043 m a.s.l. and about 60% of the basin is covered by forest (spruce in the upper parts, spruce and beech in the lower parts). The soil profile consists of brown forest soil with an unsaturated sorption complex. The soil profile characteristics depend on altitude, and its depth decreases with increasing altitude, and above 1850 m a.s.l. there are only granitic and metamorphic rocks. Measurement of snow cover are carried out two and three times per winter season. These measurements have been supplemented by sampling the snow quality in order to characterise the accumulation and evolution of chemical composition in both the snow and the streamwater. Figure 1 shows the sites where snow samples were taken. The sampling points were chosen so that they can give information about the changes of the chemical composition of the snow with altitude, aspect, snow depth and vegetation as well as the water equivalent.

The area of the drainage basin of Jalovec brook is 23.40 km^2, and its altitude above sea level is in the range from 825 m to 2188 m. Approximately 49% of the basin is covered with forest (spruce). In the elevation zone 1450-1800 m a.s.l. there is an extensive discontinuous cover of dwarf pine.

There are considerable differences between regions in the type of winter periods for the duration of the snow cover (30-150 days). The predominant air movement trajectories determine the quantity and quality characteristics of winter period snowfall concerning not only the supply of the snow cover (and its accumulation/melting) but also transport of primary and secondary pollutants. The shape of basins modifies precipitation and runoff events as well as the amount and distribution of snow accumulation. The differences are caused by exposure of basins to prevailingly direction of air masses and thus also to regional and local source of pollution.

CRITERIA FOR COMPARISON OF BASINS

Because measurements of climatic, hydrologic and hydrochemical conditions in Jalovec brook basin began from winter 1987/88, for comparison between the two studied basins the following criteria were taken into consideration:

a) SO_4^- concentration and discharge conditions

The runoff conditions have a considerable influence on the transport of SO_4^{2-}. Figure 2 presents correlation statistics and illustrates graphically the streamflow and concentration over the study period from each year/basin. The relationship between concentration SO_4^{2-} and discharge (Q) has the same tendency in both basins, with an increase of flow associated with decreases in SO_4^{2-}. A closer association was found in Bystrianka basin correlation coefficients -0.89, -0.88, -0.78 for the years 1987/88, 1988/89 and 1989/90 respectively. In case of Jalovec brook the dispersion is higher, with lower correlation coefficients of -0.63, -0.72, -0.37.

b) Sulphate and nitrate transport from the basins

Basin outputs were determined using the following relation

$$q_j = \sum_{i=t_s}^{t_e} \frac{c_i\, Q_i}{B}$$

where q_j = element transport mg/m²/day; t_s = start, t_e = end,

c_i = SO_4^{2-}, NO_3^- concentrations in the stream on i-th day (mg/l),

Q_i = average daily discharge on i-th day (m³/day),

B = the area of basin (km²)

Figure 3a & b show the estimated cumulative SO_4^{2-} and NO_3^- export. The results for SO_4^{2-} transport show similar trends in both basins for the accumulation phase of winter 1987/88. In the winter seasons 1988/89, 1989/90 the cumulative transport in Jalovec brook reached the values in Bystrianka approximately after 7-10 days of delay or to express it in another way on the same date the values in Jalovec brook are lower by about 10 g/area of basin. In the winter 1988/89 the differences are smaller than this and during the snow melting phase they are nearly equal. In winter 1989/90 the transport is lower in the Jalovec brook. The runoff conditions have a considerable influence on transport of SO_4^{2-} in the basin. The cumulative transport of NO_3^- is very similar to SO_4^{2-}.

c) The ionic input (I), output (O) balance

This was the next criterion used for a comparison of the basins. From such a balance it is possible to assess which ionic components are accumulating and which are being lost from the catchment. Table 1 gives balances (I-O) for SO_4^{2-} and NO_3^-. In the Table input includes both the wet and dry depositions, and output is the content of ions in streamwater. If I > O there is an accumulation of ions in the basins.

Table 1 *Balance of sulphates and nitrates (mg. m⁻²)*

Winter period from 12.2. - 7.5	Sulphates				Nitrates			
	Bystrianka		Jal. brook		Bystrianka		Jal. brook	
	I	O	I	O	I	O	I	O
1987-88	46506	33296			14920	7903		
(I-O)	13210				7017			
1988/89	30756	74643	29457	70835	43390	31714	5776	30033
(I-O)	-43887		-41379		11676		-24257	
1989/90	27929	48210	24832	43239	14346	28385	10586	18302
(I-O)	-20281		-18407		-14039		-7717	

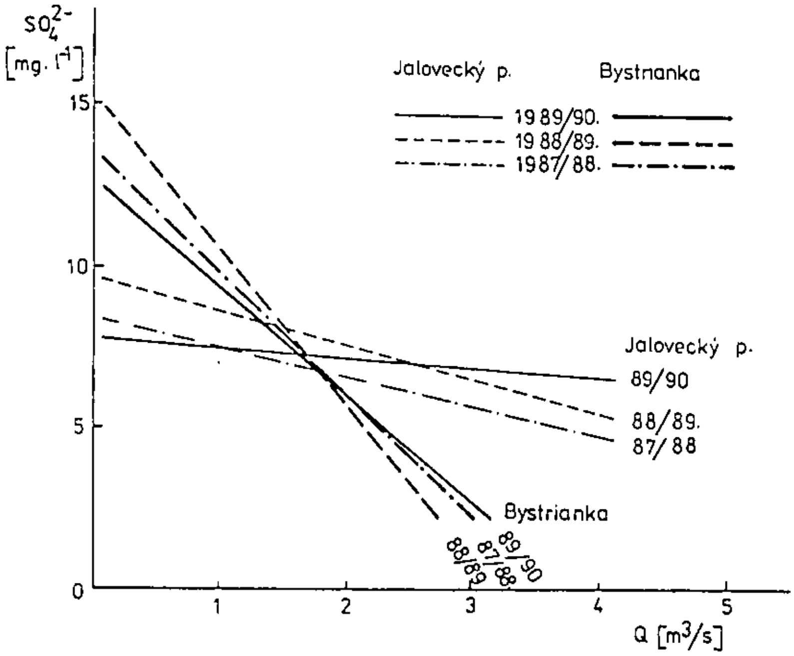

Figure 2 *Correlation between streamflow and sulphate concentrations for three winter seasons in the Jalovec and Bystrianka basins*

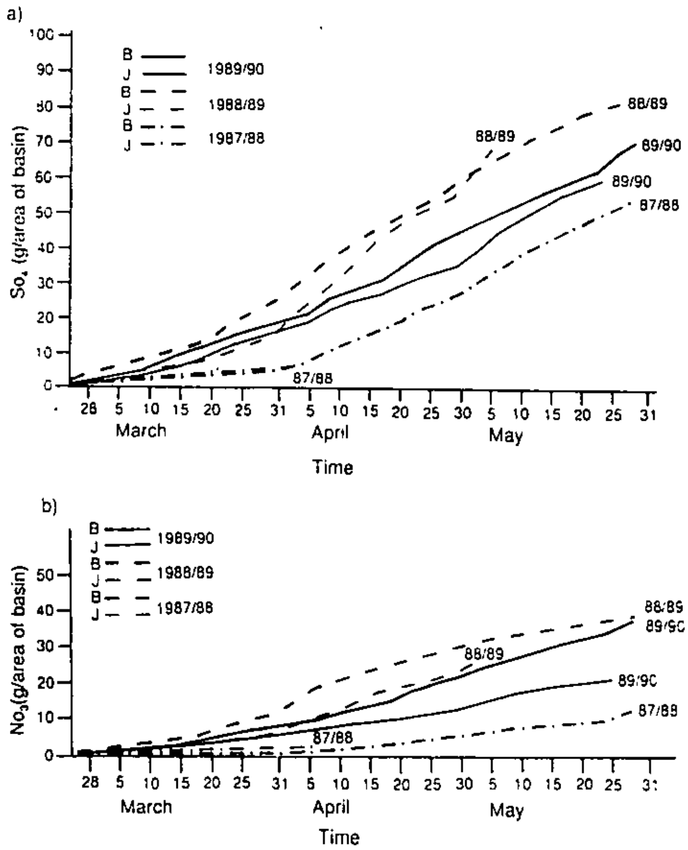

Figure 3 *Cumulative transport in streamflow from the Jalovec and Bystrianka basins of a) sulphate b) nitrate*

For both basins the SO_4^{2-} balances are negative for the last two winter periods, but the values differ. The results show smaller transport from Jalovec brook. In the winter season 1987/88 accumulation of ions occurs in the Bystrianka basin.

MODELLING SULPHATE

The amount and distribution of sulphate in the basin during winter and winter-spring period are dependent on precipitation conditions, the extent of the accumulation period and duration of significant snowmelt episodes with runoff. Using the Bystrianka IMAT model which was developed and verified in the basin of that name (Babiaková, *et al.*, 1990), we tried to quantify sulphate accumulation - washout and applied IMAT to the Jalovec brook basin. Figures 4a & b illustrate the results.

Sulphate enters the basin in the form of dry and wet deposits and essentially all sulphur leaves the basin in a dissolved form. The sulphate module depends strongly on the adequacy of the hydrological representation of the model. As our time period includes primarily the winter period, its snow subroutine is an important part of the whole model construction. Input data of daily precipitation and temperature are needed, input temperature data T_h were estimated for the hourly data measured at two stations (Brezno 600 m a.s.l., Chopok 2000 m a.s.l.). The choice of a suitable method for precipitation interpolation in such complex conditions as a mountainous basin represented a serious problem. The dependence of the precipitation on altitude is expressed by the zonal partial precipitation gradients.

The sulphate module (snow component) requires input data which represent measured values of SO_4^{2-} in both wet and dry deposits. Changes in the concentration of impurities in the snow cover are due to the SO_4^{2-} washout. The determination of washout fraction was derived from experimental and analytical results and comments regarding also other ions are described by Babiaková & Bodiš (1986).

The last step of one computation of the model is the calculation of the amount of water in the snow (mm) and the amount of sulphate in that water ($mg.m^{-2}$). These values enter the succeeding computation interval as a new state of the model. The amount of snowmelt water (water on the ground surface of basin) is the input for the runoff model. The precipitation runoff model proceeds from an empirical regression based on an auto-regressive model; the time step is 24 hours. The IMAT model (snow and runoff) was tested using the data from three winter seasons. This procedure is discussed in detail in Babiaková *et al.*, 1990.

DISCUSSION

From the description of physical and geomorphological factors and the course of processes it was shown that the basin shape is very important for the accumulation and transport of pollutants. The different shapes of the basins (in spite of equal areas) is reflected in the changes of precipitation amounts and the start of snowmelt. For applying a model an adequate interpretation of precipitation and temperature conditions (determination of altitude gradients) is required. In the case of the Bystrianka basin the method of hydrological analogy has been used, for the Jalovec brook the linear dependence method proved to be more convenient. The shape of the basin modifies weather conditions, which determine runoff patterns for individual winters.

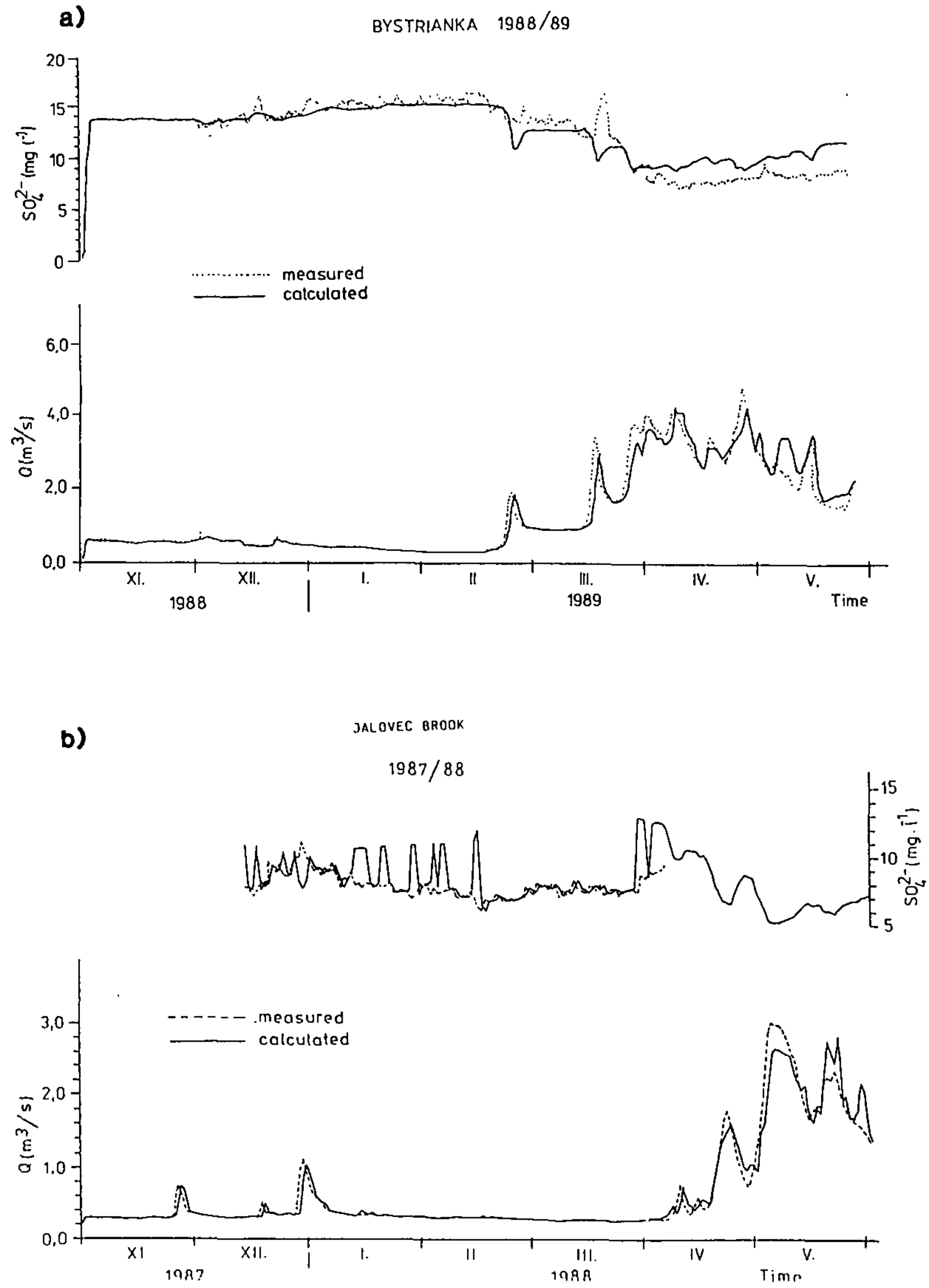

Figure 4 *Observed and simulated discharge and SO_4^{2-} concentrations for a) Bystrianka and b) Jalovec*

A greater number of altitude level bands was necessary for the Jalovec brook basin according to their different linking up during snowmelt in comparison with Bystrianka. The values of streamflow are also higher in that basin (three years of observation). The higher concentration of SO_4^{2-}, NO_3^- in Bystrianka streamflow show greater loads of ions in that basin. From the beginning of observation from winter 1984/85 the value 20.42 $mg.l^{-1}$ SO_4^{2-} (measured maximum) was exceeded two times, while in Jalovec brook it reached 12 $mg.l^{-1}$. As Figure 2 indicated, the slope of the lines also indicate the differences between the basins. The SO_4^{2-} concentrations are also higher in Bystrianka than in Jalovec brook during dilution, but later the values became similar and reached 7 $mg.l^{-1}$. The lowest measured SO_4^{2-} concentration in Jalovec brook was 5.8 $mg.l^{-1}$ during relatively higher discharge.

The main source of input is precipitation and wet and dry deposits. Due to the fact that input data into the IMAT model are reduced to 24 hour intervals, there arises a limitation for their use, according to the extent and type of basin. For every basin it is important to derive the parameters determining the similarity between the measured and computed hydrograph. Runoff processes are calculated by an empirical regression model based on autoregressive models, and concentrations in the surface water by concentration - discharge approach (C-D curve) (Wigington *et al.*, 1990). The C-D relationship refers to a group of empirical models based solely on a statistical relationship between the concentration of a solute in the stream water and the discharge. In our case the assumption has the analytical expression of a natural logarithmic function in Bystrianka basin, and for Jalovec brook a linear dependence is more suitable. With regard to the fact that C-D relationship is dependent on the accuracy of the hydrological state simulation, its results are determined by the function of the runoff model. The sensitivity of the SO_4^{2-} model to the hydrological one would be increased by using the next output of snow subroutine-concentration of water yield (concentration of melted water from snow) - calculated from washout curve - which would be entered as input into the runoff model. The advantage of applying such a model construction is its ability to simulate both processes which confirm the applicability of the model.

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15. Analysis of the hydrological role of old agricultural hillslope terraces using TOPMODEL concepts

F. Gallart, J. Latron & P. Llorens

ABSTRACT

The role of old agricultural terraces on the streamflow response of a small Mediterranean mountain catchment was investigated by comparing the actual hydrological behaviour with the behaviour simulated for conditions before terracing. The main components of the semidistributed hydrological model TOPMODEL were used first to simulate the spatial distribution of frequently saturated areas, with only a topographic calibration (ignoring the terraces), and secondly, to simulate the runoff coefficients for different soil water reserve conditions, with a baseflow calibration. The results suggest that terracing increases the volume of storm runoff as a consequence of the premature development of saturated areas.

INTRODUCTION

In Mediterranean mountain areas traditional agricultural works usually included the construction of small terraces and the drainage of runoff waters through man-made channels. As there are no data on the hydrological behaviour of such areas before terracing, we are trying to use some of the hypothesis of the TOPMODEL semidistributed hydrological model (Beven & Kirkby, 1979, Beven *et al.*, 1984) to simulate flows from 'natural conditions' i.e. as if the terraces and drainage channels were not present. These are then compared with the observed hydrological behaviour of a small man-modified basin (ERBES0303).

The relative susceptibility to saturation obtained from the analysis of the topographical structure supplied by TOPMODEL (ignoring terrace microtopography) can be compared with field observations. Furthermore, with some assessment of the baseflow recession parameters, TOPMODEL allows the prediction of relative contributing (saturated) area from antecedent conditions. It is assumed that both inputs to the model are fairly independent of the man-induced modifications.

CHARACTERISTICS OF THE STUDY AREA

The small basin (17ha) of Cal Parisa is located at 1400-1700 m of altitude in the headwaters of the Llobregat river near Vallcebre (Eastern Pyrenees) on clayey bedrock prone to gully erosion and landsliding (see Clotet *et al.*, 1988, Balasch *et al.*, 1992). The mean annual rainfall is about 850 mm, and the mean temperature is 9.2°C (Llorens, 1991).

The human modifications made in the past for agricultural use of the basin included important changes in vegetation cover, topography, and water circulation. Nowadays, most of the basin is covered by mesophile and xerophile grasslands, typical of the recently abandoned fields, with some patches of hydrophile species (mainly *Molinia coerulea*). The remainder are marginal areas, earlier abandoned, overgrown with *Pinus sylvestris* patches that tends to invade the neighbouring areas covered by grasses and bushes.

Agricultural terraces typically comprise 3 to 6 m wide flat areas and steep banks usually sheltered by man-made stone walls. This terraced topography promotes the outcrop of phreatic waters in the inner part of the terraces, where soils are absent or are very thin, causing the development of areas which are frequently saturated. In order to drain these areas and to prevent uncontrolled runoff across the terraces, a network of shallow ditches was constructed, increasing by more than 50% of total length of the drainage network (Llorens *et al.* 1992).

HYDROLOGICAL RESPONSE

The hydrological response of this basin is strongly dominated by the antecedent soil moisture conditions, storm runoff at the outlet being generated by precipitation onto saturated areas (see Llorens, 1991, Llorens & Gallart, 1992).

Under dry conditions, intense (up to 31 mm in 1 hour) or large events (58 mm in 26 hours), did not produce any runoff at the outlet, because of the high storage capacity of thick soils in the terraces. Horton overland flow is generated on some bare bedrock areas, but these are disconnected from the main drainage network so that this runoff water infiltrates when it reaches the terraced area. During wet periods, the basin shows a quick response with runoff coefficients up to 70% for a single peak during a composite event.

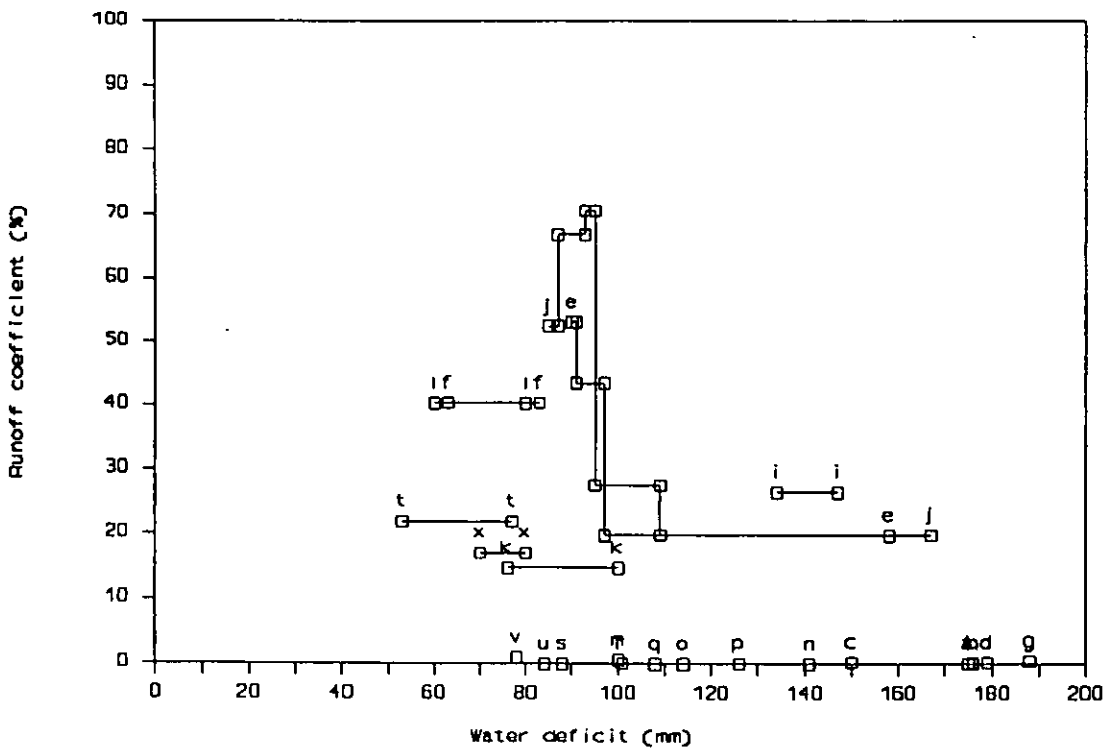

Figure 1 *Observed storm runoff coefficients for different computed soil water deficits*

Figure 1 shows the runoff coefficients for all the events with more than 20 mm of precipitation (during the period July 1989-December 1990), against the water deficit of the basin calculated with a single store model. Horizontally coupled points represent the initial and final water deficits for peaks within composite events, vertical lines link successive peaks in the same composite event. The runoff coefficients were calculated for each peak. The scattered distribution of the points can be attributed both to the water transfer delay due to the low permeability of the clayey soils, and to some limitations of the single store model.

TOPMODEL CONCEPTS AND THEIR APPLICATION

The fundamental part of TOPMODEL (Beven & Kirkby, 1979) assumes that, in a steady-state condition in which continuous rainfall provides water to flow below the surface along the hillslopes, the downslope subsurface flow rate at every point can be represented by an exponential function of the local water storage or deficit (or more strictly, transmissivity declines as a exponential function of local deficit). This basic assumption leads to the definition of a topographic index for every point of the basin Ln ($a/\tan\beta$) where a is the drained area per unit contour length and β is the local gradient, that permits the comparison among the local water deficits and with the mean water deficit of the basin.

The most interesting result of these assumptions is that the topographic index, which can be directly obtained from the topographic map, represents the relative susceptibility to saturation of every point in the catchment. This topographic index is usually handled in a lumped form to calculate the relative saturated area for every mean water deficit, only requiring the assessment of the mean saturated transmissivity (TO), and an exponential parameter (m), which can both be obtained from baseflow recession measurements (Beven *et al.* 1984). Another way to use the topographic index is in its distributed form, that permits mapping hydrological information.

For our purposes in the Cal Parisa basin, the main working hypothesis is that it is possible to set up this minimal calibration fully independent of the terraced topography. Therefore, the behaviour predicted by the model represents the natural one before the human disturbance. The first step was to use a Digital Terrain Model with a grid space of 15 m (wide enough to avoid the role of the terraced microtopography) to obtain a map of the topographic indices of the basin using a multi-directional algorithm (Quinn *et al.* 1991). The second step was to use some measurements of the baseflow recession to calibrate the other model parameters. The problem is that the modifications of soil thickness and permeability induced by terracing may influence the form of the recession curve.

QUALITATIVE DISTRIBUTED COMPARISON

Two classes of frequently saturated areas were mapped on the field with the help of the hydrophile vegetation. They correspond respectively to those where saturation is promoted by the terraces (anthropic saturated areas) and to the others were terraces do not play any noticeable role (natural saturated areas), (Llorens, 1991, and Llorens *et al.* 1992). Using a Geographic Information System, the topographic indices of these areas were determined, and their functions were compared (Latron, 1991).

Figure 2 shows the probability plots of the topographic indices for the two kinds of frequently saturated areas. It demonstrated that terrace-induced saturated areas have significantly lower

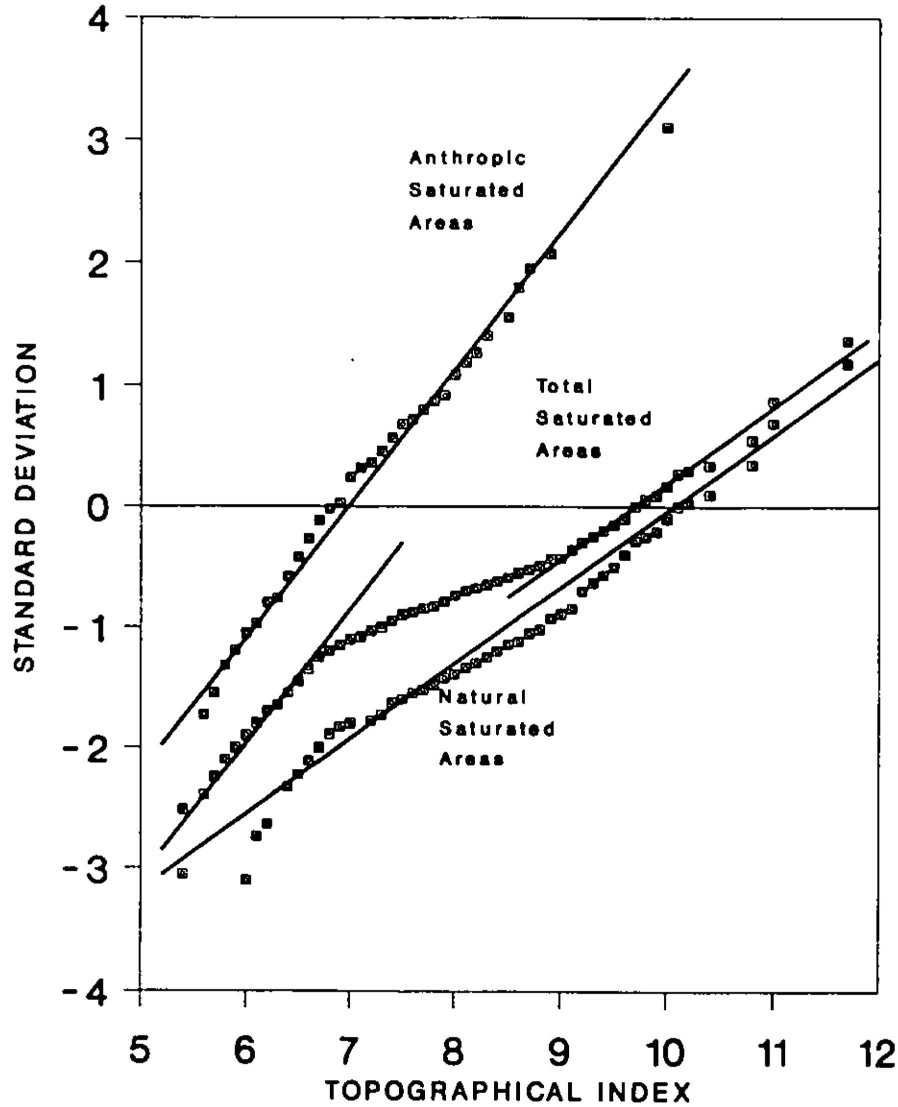

Figure 2 *Probability plot of the topographic indices of the frequently saturated areas observed in the field*

topographic indices than natural ones, and therefore these areas can become saturated under drier conditions than those predicted by the model. This result verifies the field evidence of saturation induced by terracing and confirms the usefulness of the topographic index map to analyse anomalies.

QUANTITATIVE LUMPED COMPARISON

If the terraced topography induces the formation of saturated areas in drier conditions than they would occur without terraces, the saturated contributing area of the basin for a given antecedent condition is enlarged by this modification. Actual measured runoff coefficients have to be greater therefore than those predicted by TOPMODEL assuming an undisturbed basin.

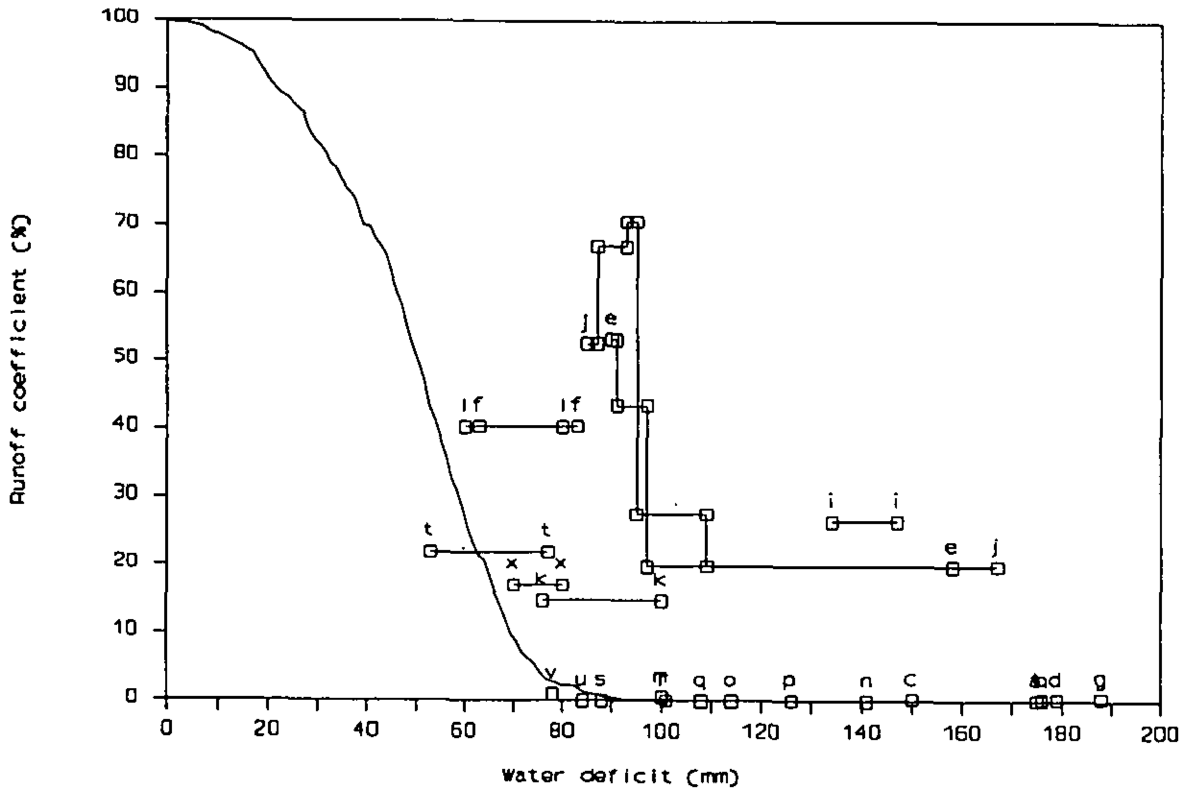

Figure 3 *Comparison of observed runoff coefficients (□) and predicted values using TOPMODEL (smooth curve) for different soil water deficits*

Figure 3 shows the performance of the model predicting runoff coefficients for different water deficit status. The form of the curve could represent a good fit to the general distribution of the points, but it is shifted about 25 mm to the left, predicting runoff coefficients significantly lower than the measured ones, for the same water deficit conditions.

In consequence, TOPMODEL would predict less storm runoff generated by saturated overland flow, counterbalanced by a significantly higher baseflow in response to the increased water storage in the basin.

DISCUSSION AND CONCLUSIONS

The main difficulty arising from qualitative analysis is the presence of some areas with high values of topographic index which appear to be rarely saturated. This seems to be the result of a higher local transmissivity due to a thicker soil, but it can also be induced by the presence above these areas of well drained terraces that harvest the subsuperificial (i.e. steeply sloping phreatic) water and prevent it from reaching them.

The quantitative analysis is limited by the enigmatic role of terraces on the baseflow recession curve. It is worth noting that the recession parameter values obtained are very similar to the ones obtained by Beven *et al.* (1984) for some subcatchments of the Hodge Beck and Wye drainage basins. Another difficulty is the actual definition of the water deficit value for a given period, in spite of its fundamental utility for any simulation.

Nevertheless, the results obtained are very consistent and suggest that this method, in spite of its simplicity, can be used for this kind of comparisons. This is especially true for the qualitative distributed analysis which offers an excellent and easy-to-use tool for analyzing anomalies of the hydrological behaviour, especially those induced by the differences in soil transmissivity.

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16. The influence of vegetal cover on flood hydrology - validation by both upscaling and downscaling simulations

G. Galea, P. Breil & A. Adang

ABSTRACT

The purpose of the approach adopted is to demonstrate the influence of differing vegetation species (forest/vineyard) on flood hydrology, modelling the Ardières and Vauxonne catchments using the GR3J conceptual model (three parameters at daily time step) and the QdF synthetic descriptive model (six regional parameters and two optimised). The results indicate that the effect of plant species on floods varies, depending on whether the precipitation is moderate (oceanic regime) or more intense (continental alpine regime).

INTRODUCTION AND STUDY AREAS

The effect of vegetation type was studied by comparing the Ardières basin at Beaujeu (54.5 km^2) and the Vauxonne basin at Buyon (49.3 km^2) which are separated by a single, common ridge. Both are located roughly 50 km N-E of the Lyons conurbation, in the northern part of the Rhône *département*, in the Beaujolais range. Each catchment area is characterized by a specific plant species: Vineyards cover 70% of the Vauxonne basin (the remaining 30% is woodland and meadow), with coniferous and some deciduous forests covering 90% of the Ardières basin. The basins have similar topography and shape.

Floods in the Vauxonne basin usually occur between November and May, on bare soil, when there are no leaves on the vines. This, of course, is not the case in the wooded Ardières basin. For the purposes of demonstration we will from now on consider species and soil a single, inseparable whole. Though less exposed to rainfall than the Ardières catchment area, Vauxonne basin floods are twice as great with much faster response to precipitation. Apart from the plant species differentiating these catchment areas, the Ardières and Vauxonne basins have several morphoclimatic characteristics in common, an essential fact in explaining the role of vegetal cover as it affects catchment area flood hydrology (Table 1). All other things being equal, the clear-cut difference between the plant species covering the Ardières basin (primarily pine) and the vine-planted Vauxonne basin is probably the most significant parameter explaining their hydrologically different regimes.

THE GR3J MODEL

Figure 1 shows the conceptual diagram of the GR3J rainfall/inflow model developed by C. Michel *et al.* (1989). It requires daily rainfall data and ten days Penman ETP input. Storage reservoir contents (S) only diminish by effective evaporation (E_S). Net rainfall (P_N) is distributed between storage reservoir (P_S) and groundwater reservoir R (P_R). Distribution is a function of $(S/A)^2$ where A represents the maximum capacity of S in millimeters.

Table 1 *Characteristics of the study basins*

CHARACTERISTICS	ARDIERES	VAUXONNE
Relief	mountainous	mountainous
Area	54.5 km^2	49.3 km^2
Total height	700 m	670 m
Compactness index	1.338	1.406
Drainage density	0.917	1.004
Woods & grassland	90%	30%
Vineyards	10%	70%
Substratum	granite	granite
Pedology	quartz sands	quartz sand
Average annual rainfall (81-87)	964 mm	820 mm

THE QdF MODEL

The QdF model which provides a descriptive synthesis of average continuous maximum flow (VCXd) is based on a synthesis of floods in the Burgundy region by Galea *et al.* (1989, 1990). The model helps forecasting VCX(T,d) floods on sites ranging from a few hectares to several hundreds of square km with no rain gauges when local parameters D (the typical catchment area flood duration according to the SOCOSE method, CEMAGREF-1980) and QIXA10 (the annual maximum instantaneous 10 years discharge) are known.

The QdF model equations defined for d (continuous duration) of $0.0003 \leq d(\text{hours}) \leq 720$ and T (average return period) are for $0.50 \leq T(\text{years}) \leq 20$:

$$VCX(T,d) = [(1/E+0.016) * \ln(T)+1/F+0.172] * QIXA10 \tag{1}$$

with $E = (2.635 * d/D) + 6.19$ and $F = (1.045 * d/D) + 2.385$

And for, $20 < T(\text{years}) \leq 1000$:

$$VCX(T,d) = VCX(T = 10,d)+[1/G * \ln(1+G * (T-10)/(10 * H))] * QIXA10 \tag{2}$$

with $G = (1.01 * d/D) + 1.84$ and $H = (2.632 * d/D) + 4.436$, where VC X (T = 10,d) is calculated by (1).

VAUXONNE AND ARDIERES CATCHMENTS: GR3J MODEL VALIDATION

A, B and C parameters representative for vegetation species

The purpose here is to identify the three parameters (A, B and C) controlling the Vauxonne and Ardières catchments runoff dynamics. To distinguish the role of vegetal species on runoff by parameter differentiation, it is important to verify that they vary little with rainfall input. Studies conducted by Adang *et al.* (1991) have shown that Ardières catchment parameters A, B and C are pseudo-independent of the year-to-year daily rainfall variations measured at the recording raingauge of St-Didier, and this is also the case with the Vauxonne basin and the recording raingauge of Blace variations. Table 2 (below) lists the parameters found after optimization (least squares method) for each year and each catchment.

Table 2 *Year to year variations in optimised parameter values*

	GR3j PARAMETERS					
Year	VAUXONNE (vineyards)			ARDIERES (forest)		
	A (mm)	B (mm)	C (j)	A (mm)	B (mm)	C (j)
1981	217	89	1.010	388	665	1.357
1982	198	69	1.033	354	639	1.336
1983	213	74	1.028	403	652	1.375
1984	219	81	1.016	330	665	1.403
1985	240	86	1.010	327	602	1.436
1986	308	95	1.001	344	665	1.424
Average	^A (mm)	^B (mm)	^C (mm)	^A (mm)	^B (mm)	^C (j)
	233	82	1.017	358	648	1.389

Effect of vegetation on daily runoff as shown by A, B and C

A, B and C parameter averages for the Ardières catchment area differ significantly from Vauxonne basin averages (Table 2). The capacity of the (S) and (R) storage reservoirs in the Ardières catchment area are eight times lower than those in the Vauxonne basin, causing higher flood volumes and maximum flow rates.

The linear rainfall distribution function operand when expressed as a discrete value (1) can be written:

$$Q_j = \int_{j-1}^{j} q(t)dt = (3j^2 - 3j + 1)/C^3, \qquad (3)$$

where j represents a time step of one day.

When applied to daily rainfall, we find that in the Vauxonne catchment 95.3% of precipitation volume is directed to the R reservoir the same day and 4.7% the next. In the Ardières catchment area, only 37.7% of precipitation volume is directed to the reservoir the same day, with as much as 62.7% arriving there the next.

Using the GR3J conceptual model demonstrates that coniferous and deciduous forest soil as compared to bare vineyard soil (no fallen leaves), has a retaining effect on overall runoff.

FORECASTING FLOOD QUANTILES

Statistical tools

For the rest of this demonstration, the plant species effect will be expressed in terms of flood quantiles. Statistical tools used are defined as follows:

a) Measured or simulated flow rate statistics

Flow rate samples (VCXd) in excess of a certain threshold and defined for several uninterrupted periods of time d (1sec. ≤ d ≤ 30days) have been adjusted for the 2n highest values (n = number of years) to a general equation renewal model (binomial: Poisson distribution + exponential distribution):

$$VCX(T,d) = Gq(d) * \ln(T) + VCXo(d) \quad (4)$$

while defining for 0.5 ≤ T(years) > 20 with, Gq = flowrate gradex, VCXo = position parameter

b) Extrapolation of observed or simulated rare frequency flood quantiles

- *for d > D/2 and T > 20 years*

(where D is the SOCOSE model flood time characteristic)

The extrapolation form (5) at rare frequencies of observed flowrate samples by maximum rainfall gradex was established by Michel (1982):

$$VCX(T,d) = VCX(T = 10,d) + Gp(d) * \ln[1 + Gq(d) * (T-10)/(Gp(d) * 10)] \quad (5)$$

where Gp(d) = the uninterrupted period d maximum rainfall gradex

- *for d = 1 second (instantaneous) and T > 20 years*

QIX maximum instantaneous flowrates at rare frequencies is extrapolated from the relation:

$$QIX(T) = \lambda(Cq,Cr,T) * \hat{r} * VCX(T,d = D) \quad (6)$$

where $\hat{r}$ = the average of sample r = QIX/VCXD

The λ variable, according to Colin *et al.* (1977) depends on the VCX_D (C_q) variation factors, on r (Cr) and on T.

Applying the statistical tools

Using the 1973-1988 rainfall data at the Blace and St-Didier weather stations GR3J simulations produce daily runoff time series for the Vauxonne and Ardières catchment areas at Buyon and Beaujeu respectively.

A comparison of flood quantiles deduced (Figures 2 and 3) by applying the statistical tools to runoff time series (1973-1988) both simulated and observed in the Vauxonne (1981-1989) and Ardières basins (1969-1989) demonstrates the adequacy of the GR3J model.

QdF MODEL VALIDATION

Statistical analysis of observations permits us to define local characteristics D and QIXA10 for each catchment area (Table 3, below).

Table 3

CATCHMENT	QIXA10 (m^3/sec.)	D (hours)
VAUXONNE	28.5	13
ARDIERES	14.6	27

Knowing D and QIXA10, applying equations (2) and (3) produces transferred flood quantiles. Figures 2 and 3 show the adequacy of the QdF and GR3J models for the Vauxonne and Ardières catchments. Figure 4 shows the QdF model's excellent suitability for forecasting instantaneous Vauxonne and Ardières basin runoffs.

VEGETAL COVER EFFECTS ON FLOOD QUANTILES

Synthetic precipitation selection

Both the GR3J and QdF models were then used to simulate runoff for each plant species from identical 'synthetic' precipitation inputs. During this simulation, we allowed for pluviometric regime (more or less moderate) to quantify the vine/forest vegetal contrast effect on flood quantiles in particular. To do so, we selected the weather stations of Nantes and Chartreux (N-E of Grenoble), which have both been administered by Météo-France for the past 15 years (1973-1987). The Nantes weather station is typical of a moderate, oceanic type of rainfall regime, while Chartreux exemplifies the more intense, continental alpine regime.

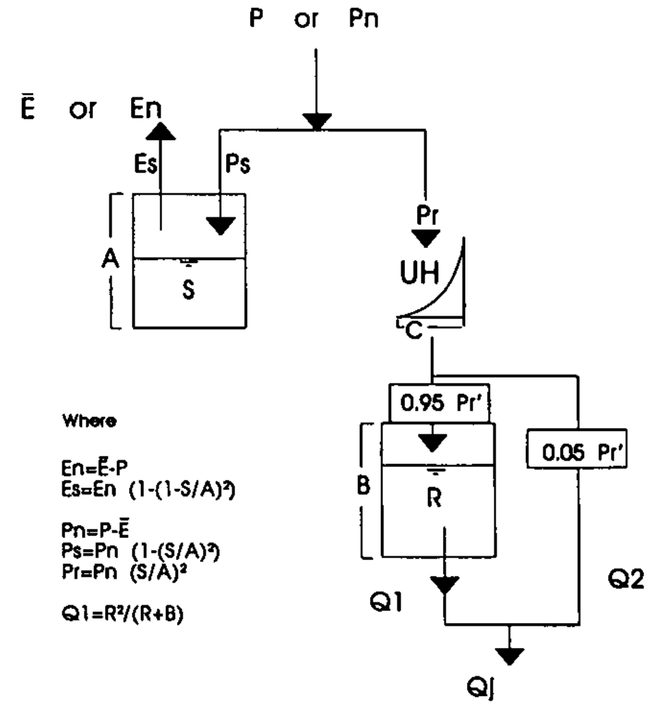

Figure 1 *Conceptual diagram of the GR3J lumped model*

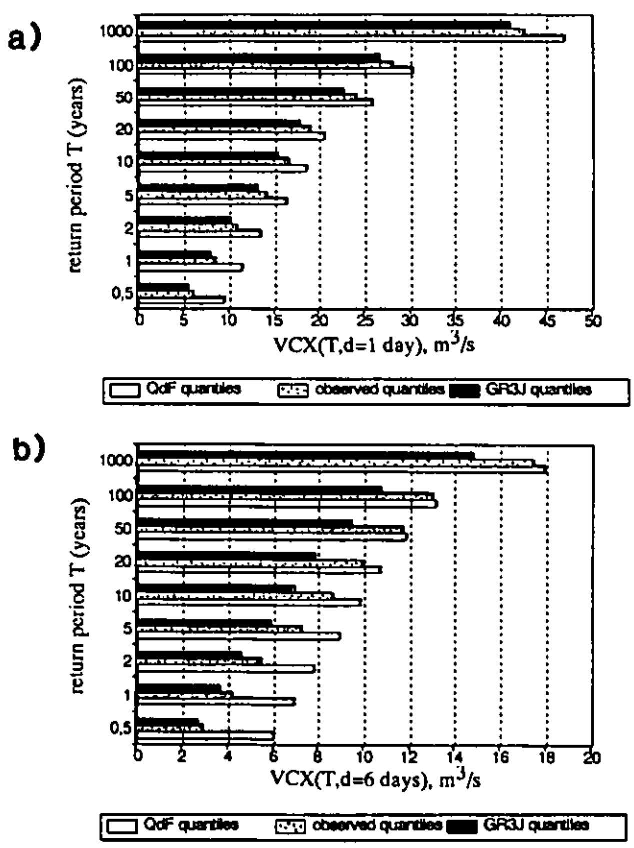

Figure 2 *Observed and modelled flood quantiles for the VAUXONNE catchment using the GR3J and QdF models a) one day duration, b) six days duration*

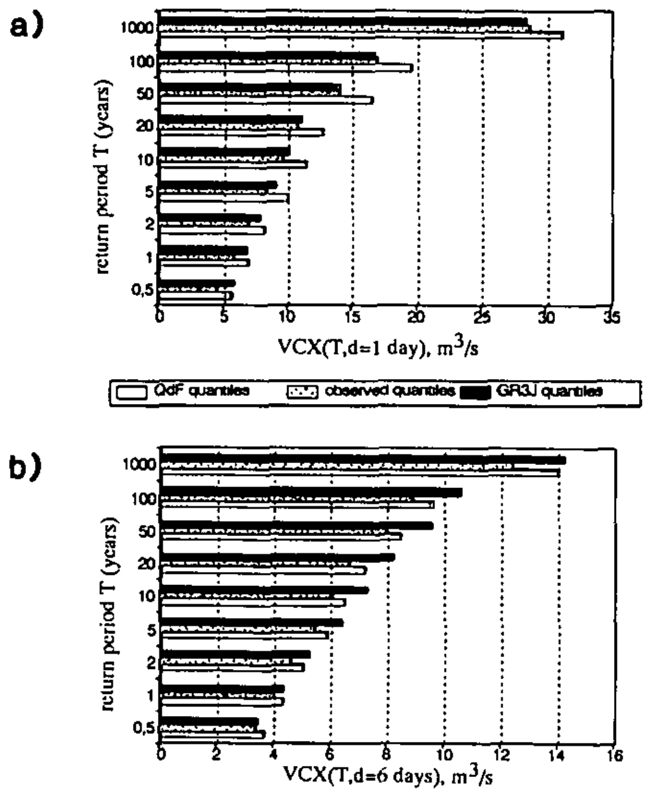

Figure 3 *Observed and modelled flood quantiles for the ARDIERE catchment using the GR3J and QdF models a) one day duration, b) six days duration*

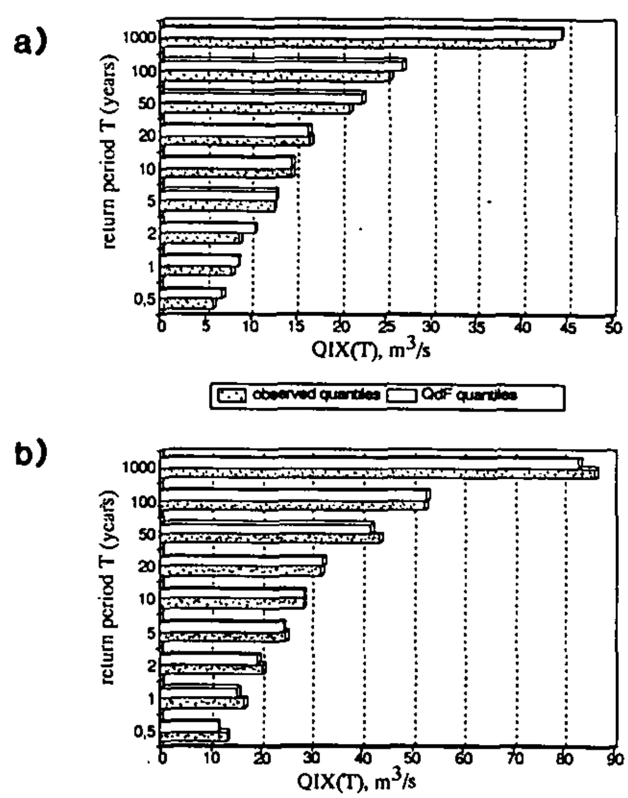

Figure 4 *Validation of QdF model for an instantaneous duration for a) Ardiere, b) Vauxonne catchments*

Rainfall regime characterization

Figures 5 and 6 show how regimes differ as regards annual rainfall and maximum rainfall quantiles (one day and three days) for observable frequencies ($0.5 \leq T$ (years) ≤ 20). The Nantes weather station had an annual average of 796 mm between 1973 and 1987, whereas the Chartreux weather station had 2 042 mm.

GR3J and QdF daily flood quantiles comparison

Figures 7 and 8 compare daily flood quantiles produced by the GR3J and QdF models for each catchment and a given raingauge. For the QdF model, local characteristics D and QIXA10 were estimated to match as closely as possible flood quantile orders of magnitude ($1 \leq d(days) \leq 30$) deduced from the statistical analysis of daily runoff time-series simulated by the GR3J model (Table 4).

Table 4

CATCHMENT	WEATHER STATION	QIXA10 (m^3/s)	D (hours)
VAUXONNE	Nantes	15	15
	Chartreux	55	11
ARDIERES	Nantes	7.5	40
	Chartreux	32	27

Figures 7 and 8 indicate that, regardless of plant species, passing from a moderate rainfall regime (Nantes - Figure 6) to a more intense regime (Chartreux) produces daily flood quantiles roughly four times as great ($0.5 \leq T(years) \leq 20$).

THE VEGETAL SPECIES EFFECT ON FLOOD QUANTILES

Selecting a flood quantile unit of measure (m^3/s)

Flood quantiles for each plant species are expressed in m^3/s and related to basin area. The fact that the Ardières catchment area is 5.2 km^2 greater than the Vauxonne basin was not considered likely to bias quantile comparisons to any significant extent. For all intents and purposes, then, the reference area is taken to be 50 km^2.

Simulating the effect of vegetal cover on flood quantiles of a given duration

a) *instantaneous flood quantiles (QdF)*

Knowing D and QIXA10 for each catchment, the QdF model permits the simulation of instantaneous floods under given rainfall conditions. A change of rain regime from an oceanic to a continental alpine one (Figure 9) affects forest-type flood quantiles (increasing by a factor 4.3) more than vineyard-type flood quantiles (increasing by a factor 3.7). In other words (Figure 9), passing from a moderate regime to a more intense one causes the instantaneous flood quantile regulating capacity of the forest to diminish by a ratio of 2 to 1.72.

b) daily flood quantiles (GR3J)

Figure 10 represents the evolution of maximum daily runoff quantiles and evapotranspiration periods for each plant species in a given rainfall regime. As before, we see that the regulatory role of the forest during the entire evapotranspiration period is less pronounced under intense (continental alpine) rainfall regimes than under moderate (oceanic) regimes.

With a view to the extrapolation hypothesis Equation 5 of rare frequency flowrates ($T>20$ years), it would seem that, compared to the vineyard, only the 1000 year average return period shows a modest regulatory role on the part of the forest, especially under more intense rain regimes (1.39 to 1.28).

c) preliminary conclusion

At instantaneous intervals, the forest, when compared to the vineyard, has a major peak-shaving effect on peak flowrates for all return periods, especially under moderate rainfall regimes. At daily intervals the tendency persists, though the regulatory role of the forest becomes more modest during low ($T<1$ year) and high ($T<50$) return periods.

Simulating the influence of vegetation on 5 and 100 year flood quantiles of differing durations

Figures 11 and 12 show the plant species effect on respectively a 5-year and a 100-year flood quantile of different durations (1sec $\leq$ d $\leq$ 30days) for different rainfall regimes. Under a moderate rainfall regime, the forest runoff regulating capacity lasts for as long as 30 days. This would not appear to be the case at more intense regimes or for durations in excess of three days. We therefore feel warranted in considering that plant species (vineyard/forest) cause relatively comparable runoffs.

CONCLUSION

Two very different models (the GR3J conceptual global model and the QdF descriptive synthetic model) were used to model runoff from two small Beaujolais catchments, and results strengthen the theory of plant species affecting flood hydrology.

The GR3J conceptual global model reveals certain regulatory aspects of forests on flooding as compared to vineyards. One of these, a much slower release of net rainfall by storage reservoir S (A = 358 mm against 233 mm for vineyards), contributing 37% of inflow the same day and 63% the next, instead of 95% in the case of the vineyard and the large same-day storage capacity of the R reservoir (B = 648 mm against 82 mm for vineyards), is preponderant in flood generation.

Statistical processing of model GR3J and QdF outputs for moderate, oceanic precipitation regime-type or more intense, continental alpine rainfall volume simulations demonstrate the effect of vegetal cover on flood quantiles, all other conditions being equal. Results show that forest soil in a small catchment area of 50 km^2 in the Beaujolais region, as compared to a vineyard soil, has a greater flood regulating capacity when the rain regime is less intense and the time duration d of runoff quantiles VCX(T,d) is short. We have established that the forest has a major peak-shaving influence on flood peaks for all return periods, which is less pronounced in the case of non-instantaneous quantiles.

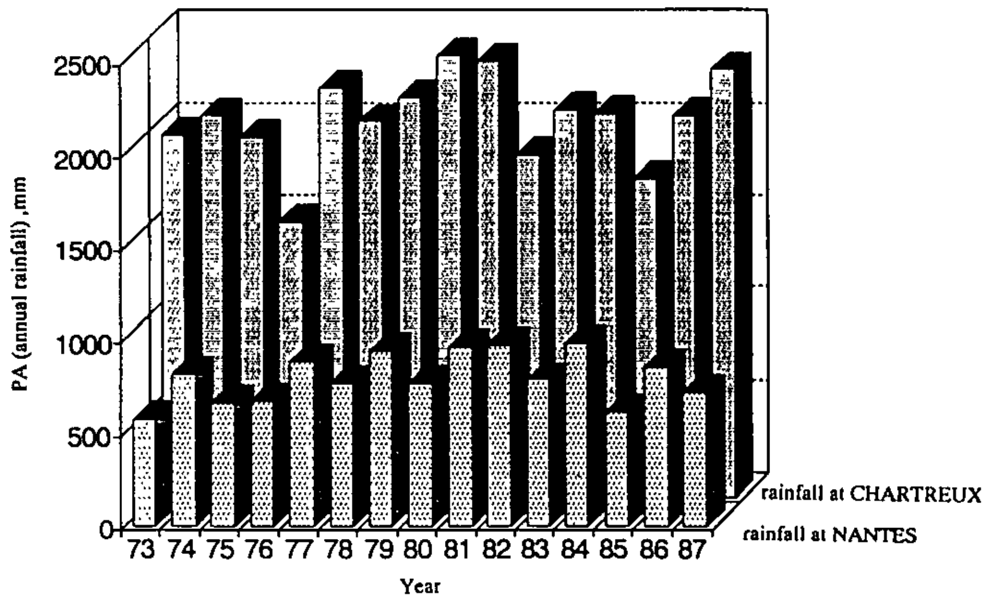

Figure 5 *Comparison of annual rainfall at Nante (oceanic regime) and Chartreux (continental)*

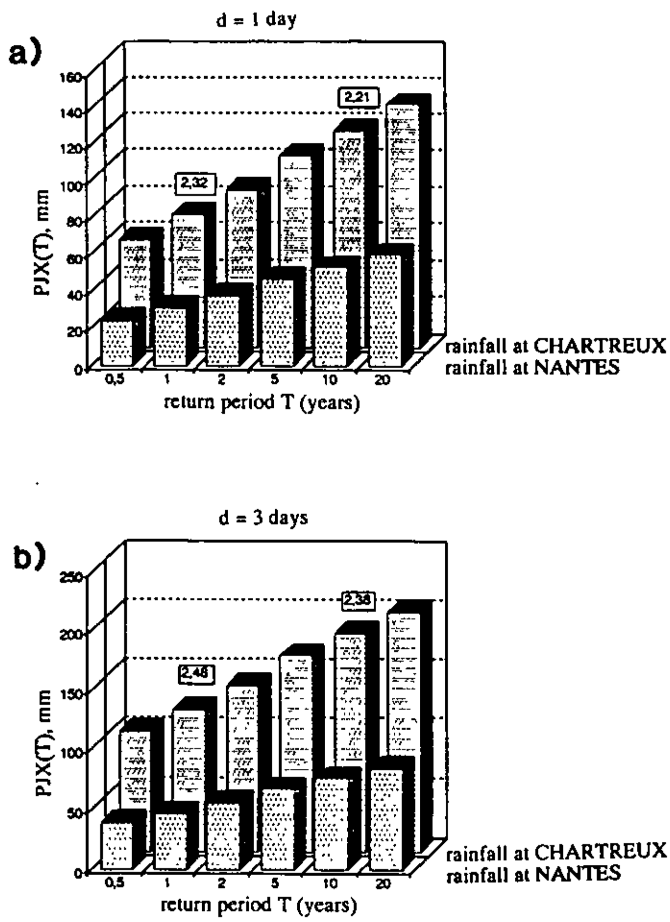

Figure 6 *Comparison of rainfall quantiles at Nantes and Chartreux for durations of a) one day, b) three days*

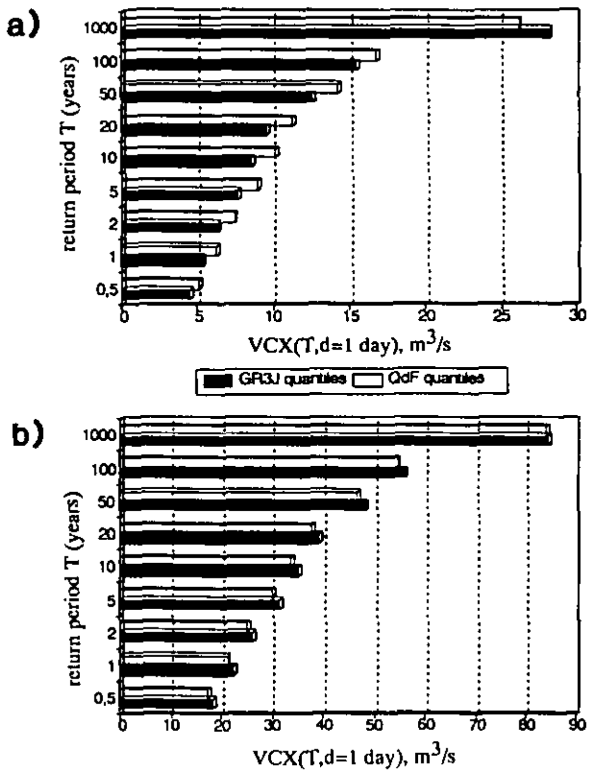

Figure 7 *Comparison of daily flood quantiles for vineyard simulated by the GR3J and QdF models using the precipitation data from a) Nantes, b) Chartreux*

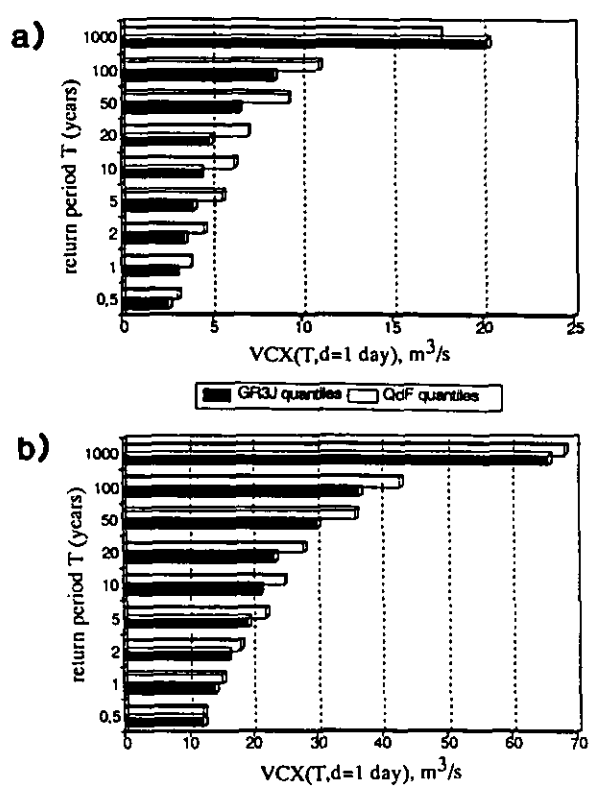

Figure 8 *Comparison of daily flood quantiles for forest simulated by the GR3J and QdF models using the precipitation data from a) Nantes, b) Chartreux*

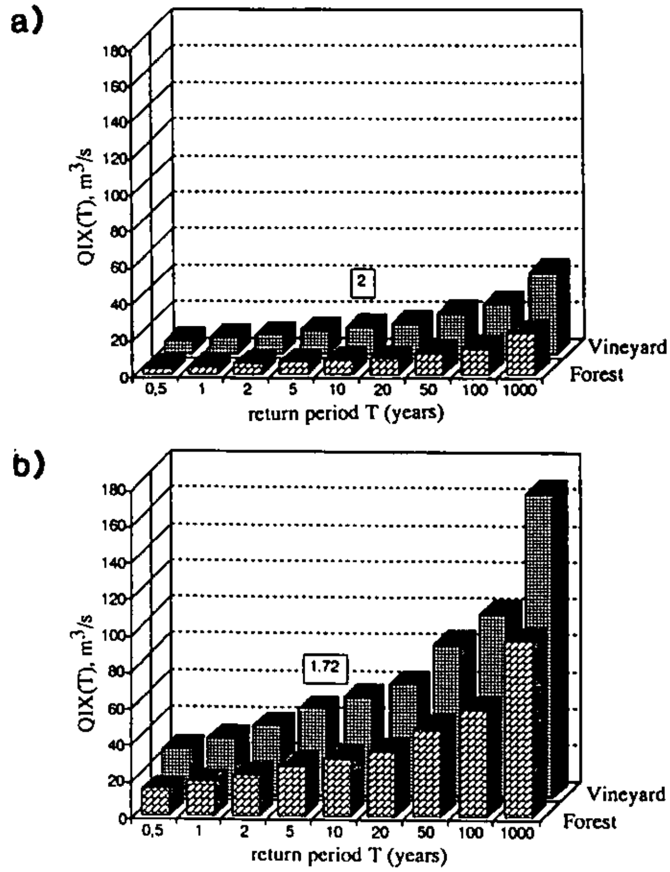

Figure 9 *QdF model simulated instantaneous flood quantiles for forest and vineyard using the precipitation data from a) Nantes, b) Chartreux*

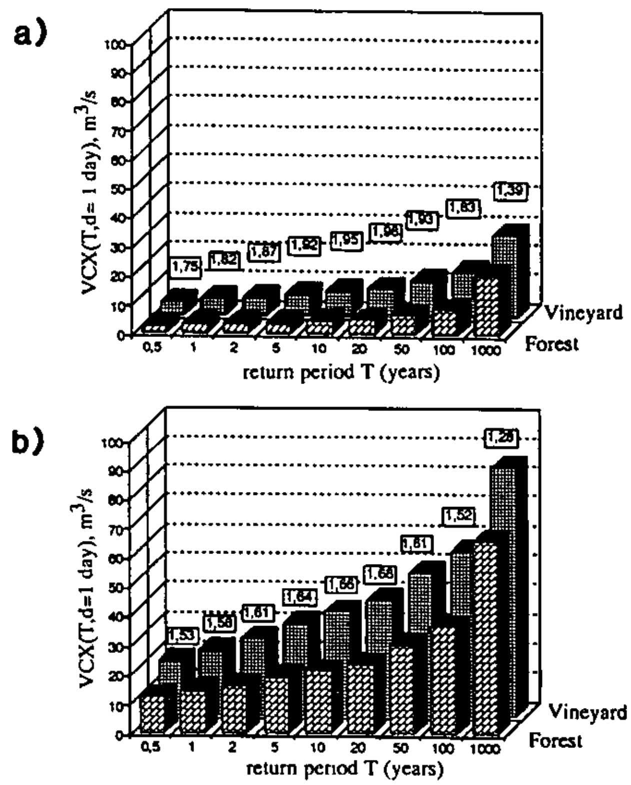

Figure 10 *GR3J model simulated daily flood quantiles for forest and vineyard using the precipitation data from a) Nantes, b) Chartreux*

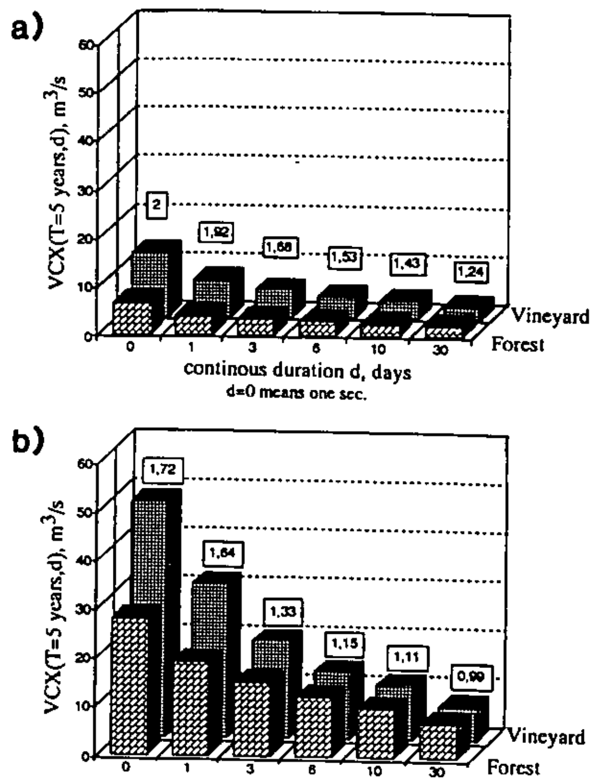

Figure 11 *Simulated 5 year return period flood quantiles, using the QR3J model, for forest and vineyards using precipitation data from a) Nantes, b) Chartreux*

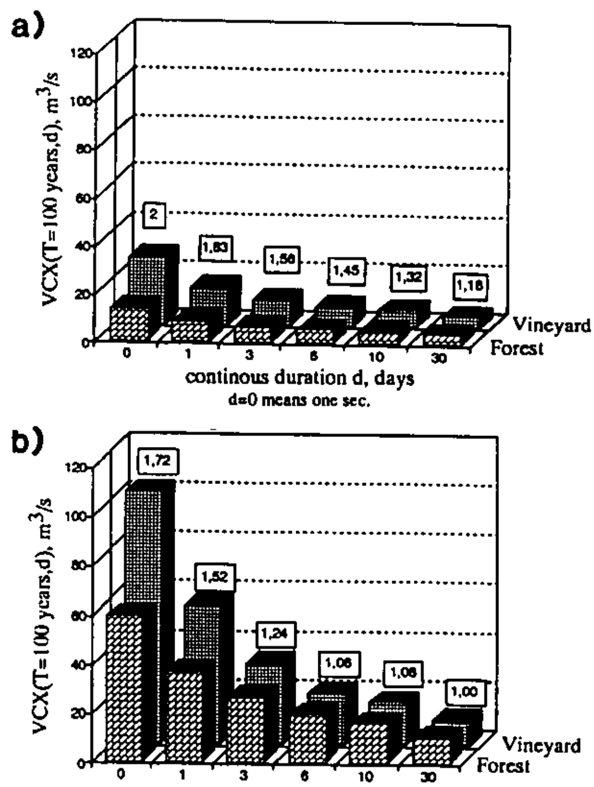

Figure 12 *Simulated 100 year return period flood quantiles, using the GR3J model, for forest and vineyards using precipitation data from a) Nantes, b) Chartreux*

ACKNOWLEDGEMENTS

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17. Comparisons of catchments in Bohemia with the aim to predict floods on ungauged catchments

S. Blazkova & B. Kulasova

ABSTRACT

Fifteen gauged basins (2 to 350 km²) in three different regions of Bohemia are compared as to precipitation, runoff coefficients and unit hydrograph parameters, in order to improve methods of design flood determination on ungauged basins. The isolines of mean annual maximum 1-day rainfall totals, reduced on appropriate rainfall duration, give good results when used for flood prediction, with the exception of one catchment where snow plays an important role. Runoff coefficients have been calibrated to obtain the flood peaks with return period of 100 years. Detailed comparison of the effect of space-time rainfall pattern on unit hydrographs has been performed on four basins. Some comparisons with basins abroad are suggested.

INTRODUCTION

The catchments used in this study are given in Table 1, listing their areas, the abbreviations used in the Figures and sources of data. The percentage of urbanized area varies between 0 and 9 per cent.

Table 1 *List of basins*

Abb.	Fig.	Site	Stream	Area (km²)	Source of data
BOH	1	Bohumilice	Sputka	104.3	Balek (1975), Janoušek and Mates (1980)
LNR	1	Lenora	Teplá Vltava	175.77	CHMI (1992)
CHLV	1	Chlum-Volary	Teplá Vltava	346.87	CHMI (1992)
CKV	1	Černý Kříž	Studená Vltava	104.13	CHMI (1992)
CIH	2	Cihelny	Teplá	286.14	Ohre River Board, Krenikova (1987), Barborik and Chamas (1970)
VIL	3	Vilěmov	Jizera	6.29	CHMI (1992)
DSYT	3	Dolni Sytová	Jizera	321.40	CHMI (1992)
JH	3	Janov-Harrachov	Mumlava	50.92	CHMI (1992)
DSTE	3	Dolni Štěpanice	Jizerka	44.86	CHMI (1992)
BP	3	Bilý Potok	Směda	26.13	Krejcova (1992)
UHL	3	Uhlířská	Černá Nisa	1.87	Pivrnec and Bicik (1992)
BL	3	Blatny rybnik	Blatný potok	4.56	Pivrnec and Bicik (1992)
KR	3	Kristianov	Kamenice	6.62	Pivrnec and Bicik (1992)
SI	3	Smědava I	Bílá Smědá	3.72	Pivrnec and Bicik (1992)
SII	3	Smědava II	Cerná Smědá	4.74	Pivrnec and Bicik (1992)

PRECIPITATION

The determination of statistical characteristics of annual maximum of one-, two- and three-day precipitation totals has been carried out for the whole of Bohemia. Daily precipitation series for 1055 stations were used. For computing the mean annual maxima a minimum of 10 years of data was used regardless of gaps in measurement, whilst for coefficients of variation (Cv) and skewness (Cs) the minimum was 30 years. A three parameter log-normal distribution was fitted to the data. The results are the maps of isolines of mean annual maxima and the coefficients of variation of annual maxima. Ratios of Cs/Cv were estimated for larger hydrological regions (Kulasova *et al.*, 1985). The isolines for the regions of interest in the present study are given in Figures 1, 2 and 3. The computed one-day precipitation totals with the return period of 100 years (P_{100}) are listed in Table 2.

The Sputka and Upper Vltava Basins (southern Bohemia) are situated on the lee side of the Sumava Mountains. The increase of rainfall with altitude is particularly apparent in the Sputka Catchment (Figure 1). The Tepla Basin (near Karlsbad) is also on the lee side. The precipitation totals are even lower and uniformly distributed over the catchment area (Figure 2). Moreover, they are the snowmelt-with-rain events or the events with rainfall soon after the disappearance of snow, when the catchment is still wet, which are important for flood formation in this catchment. The Jizera Mountains (northern Bohemia) are, from the precipitation point of view (both volumes and intensities), an extreme area in Bohemia (Figure 3).

For flood prediction the one-day rainfall totals were reduced to the appropriate duration using the equation of Hradek (1991), and tested on probable one-hour intensity for large storms depending on the catchment area (Hauser in Kotrnec, 1976).

RUNOFF COEFFICIENTS

The runoff coefficients (C) considered here are determined as the ratio of effective runoff volume P_e to the causative total areal rainfall.

For the Sputka experimental catchment "observed" runoff coefficients (C_{obs}) have been computed for 25 events. The following table shows the values for different return periods of the flood peak (N) beginning with N = ½ year.

N [yr]	½	½-1	1	1-2	2	2-5	10
C_{obs}	0.12	0.14	0.18	0.10	0.22	0.13	0.14
	0.09	0.14	0.13	0.15			
	0.03	0.05	0.04				
		0.10					

The 10-year peak was caused by a rainfall total equal to P_{100} (123 mm).

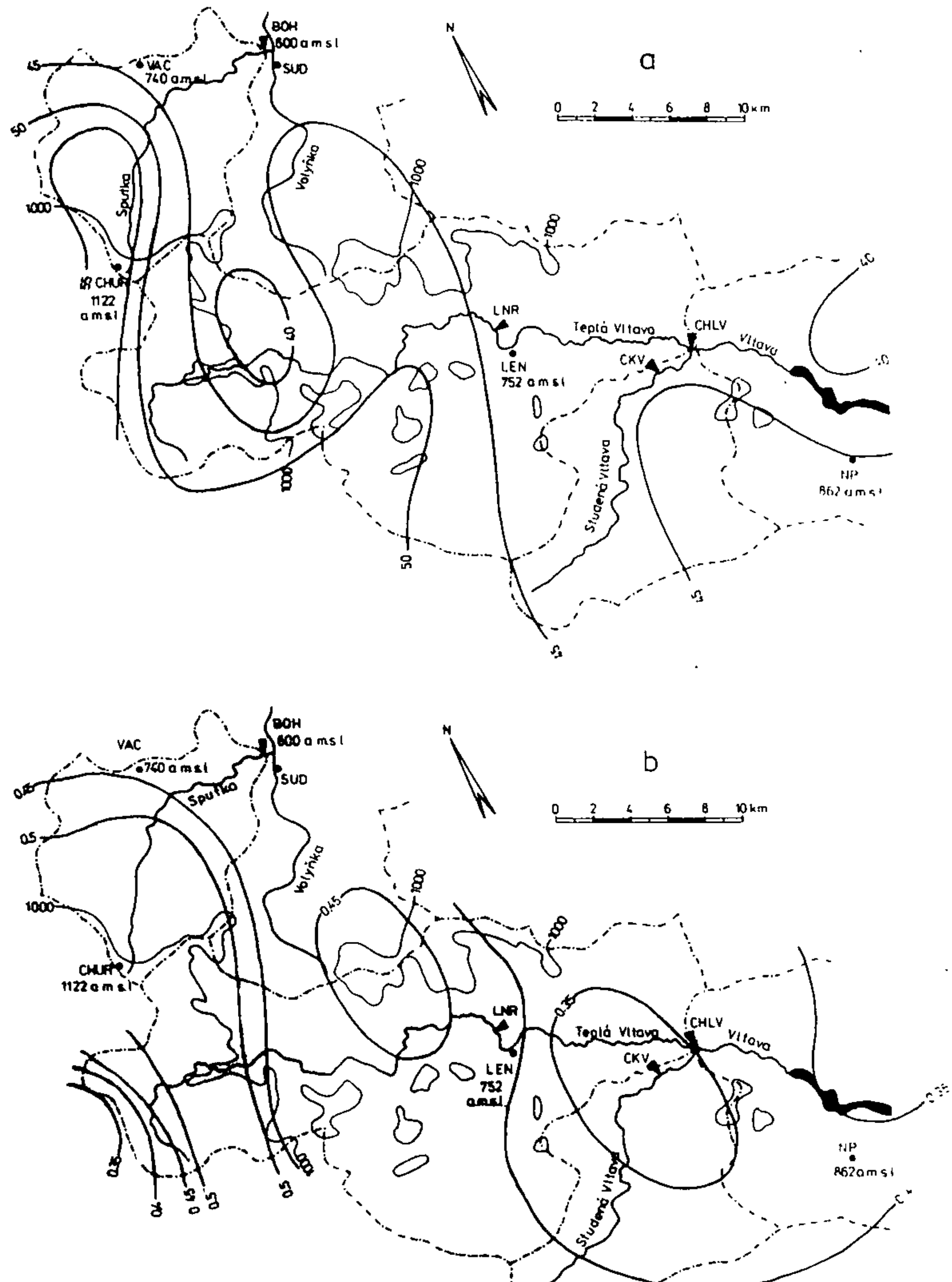

Figure 1 *The Sputka and the Upper Vltava basins with the 1000 m a.m.s.l. contour line and: a - the isolines of mean annual maxima of one-day precipitation totals [mm]; b - the isolines of coefficients of variation of annual maxima of one-day precipitation totals (Kulasova et al., 1985)*

Table 2 *Computation of Q_{100}*

Site	P_{100}	UH identification: No. of events	UH identification: Q_N of select.	UH Parameters: Nash N	UH Parameters: Nash K	UH Parameters: chan.+1res T_{ch}	UH Parameters: chan.+1res K_{ir}	C_{obs}	for Q_N	Q_{100} model	C_{calib} to get	Q_{100}
	(mm)				[h]	[h]	[h]			[$m^3 s^{-1}$]		[$m^3 s^{-1}$]
BOH	125	27	Q_{10}	2.4	3.6			0.14	Q_{10}	34.5	0.34	82.8
LNR	119	1	$Q_{½-1}$	3.3	3.0			0.46	$Q_{½-1}$	174	0.35	141
CHLV	99	1	Q_1	7.1	3.3			0.21	Q_1	88.3	0.40	174
CKV	99	1	Q_1	1.5	7.3	[2.1	9.0]	0.21	Q_1	31.1	0.57	94.1
CIH	68	4	$Q_{<½}$	2.9	3.7			0.23	Q_{1-2}	72.6	(0.72)	227
			Q_{2-5}	2.6	6.0			0.28	Q_{2-5}	62.5	(0.90)	
VIL	178	6	Q_{100}			2.1	4.0¹⁾	0.50	Q_{100}	367	0.45	330
DSYT	140	5	Q_{5-10}			2.9	4.2	0.52	Q_{5-10}	739	0.33	463
JH	140	2	Q_5	[1.6	4.5]	1.4	5.6	0.76	Q_5	147	0.73	140
DSTE	143	2	Q_1			2.0	5.0	0.34	Q_2	62.8	0.65	120
BP	190	4	$Q_{<1}$			2.4	2.4	0.74	Q_{1-2}	168	0.65	144
UHL	187	1	Q_{5-10}			0.2	0.4²⁾	0.42	Q_{5-10}	13	0.75	23
BL	271	1	Q_{20-50}			0.8	1.0²⁾	0.46	Q_{20-50}	39.3	0.40	31
KR	271	1	Q_{10-20}			1.1	1.3²⁾	0.65	Q_{10-20}	68.4	0.72	76
SI	206	1	Q_{5-10}			1.0	0.7²⁾	0.67	Q_{5-10}	39.8	0.67	40
SII	206	1	Q_1			0.9	1.2²⁾	0.36	Q_1	22.1	0.75	45

¹) modified, ²) Rough indentification on hourly data; [ ] not used; ( ) not realistic

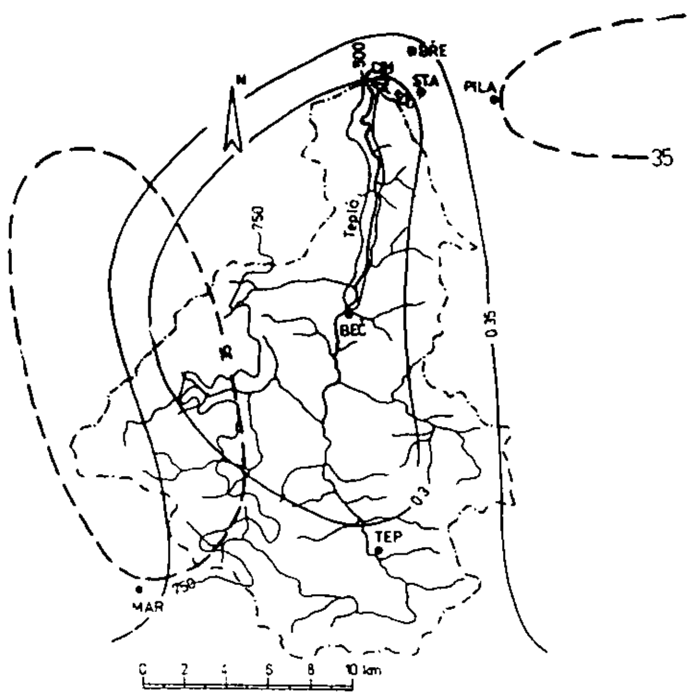

Figure 2 *The Tepla basin with the 750 and 500 m a.m.s.l. contour lines, the isolines of mean annual maxima of one-day precipitation totals [mm] (dashed lines) and the isolines of coefficients of variation of annual maxima of one-day precipitation totals (Kulasova et al., 1985)*

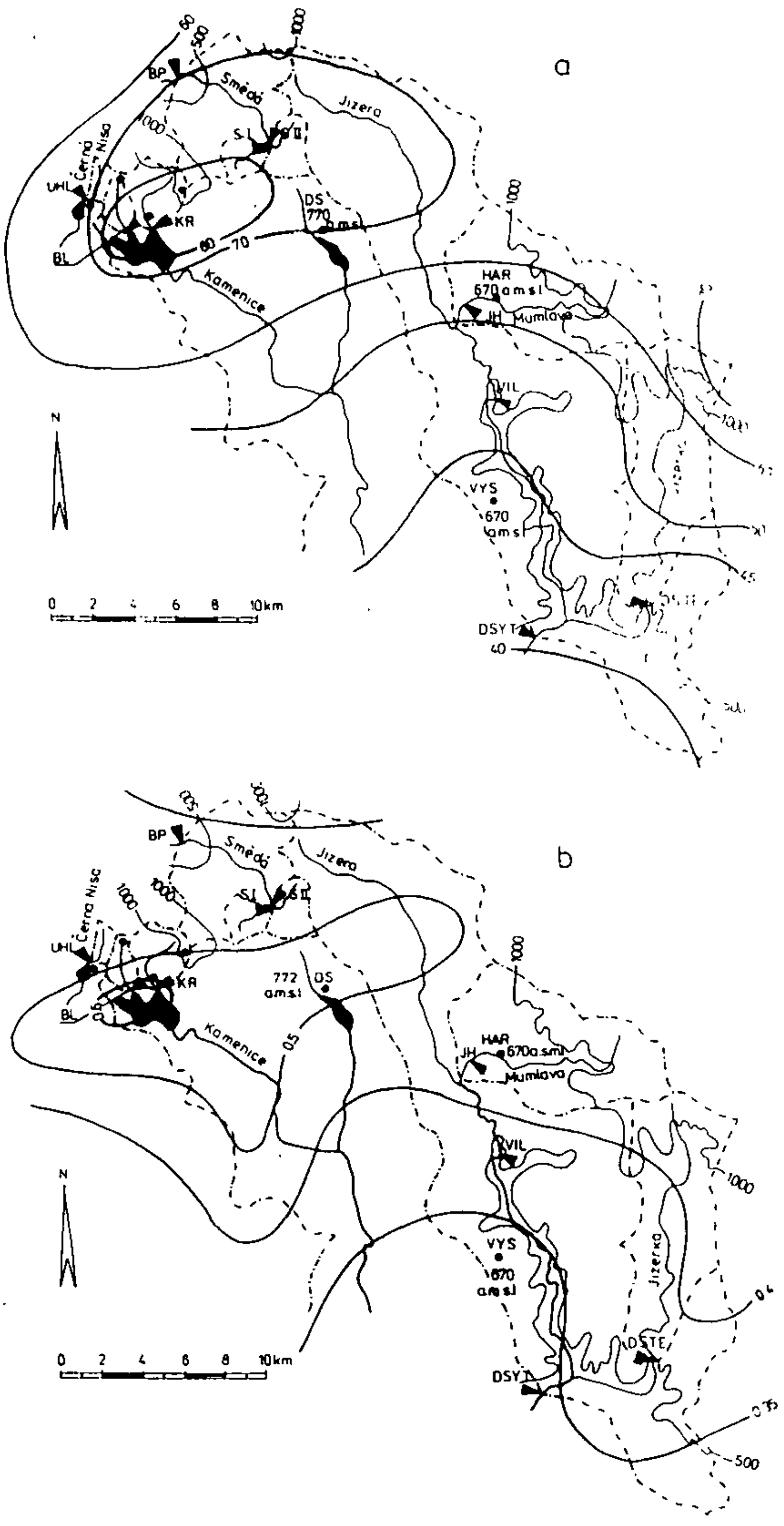

Figure 3 *Basins in the Jizera Mountains with the 1000 and 500 m a.m.s.l. contour lines, and: a - the isolines of mean annual maxima of one-day precipitation totals [mm]; b - the isolines of coefficients of variation of annual maxima of one-day precipitation totals (Kulasova et al., 1985)*

For the Volynka catchment (383 km^2), which includes the Sputka catchment, there is a 10-year data set for coaxial correlation (CHMI, 1992). The runoff coefficients for the rainfall totals over 30 mm are as follows:

P[mm]	30-40	40-50	50-56	95
C_{obs}	0.06	0.05	0.10	0.19
	0.06	0.06	0.25	
	0.07	0.06		
	0.09	0.09		
	0.13			

In the Tepla catchment four rainfall-runoff events were available, but only one of them was large (N=2-5). There is, however, a coaxial correlation data set (for the period without snow) over 33 years, from which runoff coefficients for larger events could be computed (Barborik & Chamas, 1970, Krenikova, 1987):

N [yr]	½	½-1	1	1-2	2-5
C_{obs}	0.11	0.19	0.19	0.15	0.28
	0.17	0.11	0.14	0.23	
	0.10	0.11	0.16		
	0.14				
	0.12				

The July event with N=1-2 and C_{obs}=0.23 had both the 3-day and 1-day rainfall totals recorded at one of the raingauges close to N=100, in the other station the totals were lower but the centre of the storm was probably measured accurately enough. This was not the case for four other important events where the areal rainfall was apparently underestimated because of insufficient number of stations and C_{obs} would then be over 0.5 or even 0.8 consequently. These events have been excluded. The early April event with N=2-5 and C_{obs}=0.28 occurred just after the snow from the upper part of the basin had disappeared.

The problems of determining runoff coefficients are far greater in the Jizera Mountains. Runoff is a considerable portion of the rainfall and therefore an inaccurate determination of areal rainfall for individual storm events may in many cases leads to useless results. When the centre of storm is not observed by any gauge the ratios of total runoff to total rainfall for a flood event are often bigger than one and the C_{obs} can easily be over 0.8. This type of error was observed on Smeda at site BP (26.13 km^2) by Krejcova (1992) who mostly had to use the rainfall data from an adjacent catchment, but also by the present authors on Jizera at site VIL (146 km^2). The C_{obs} coefficients for the catchments with more events available and rainfall stations within the catchment are given below:

N [yr]	½	½-1	1	1-2	5-10	10-20	100
VIL		0.38	0.21	0.64		(0.82)	0.50
			0.30				
DSYT	0.21	0.12	0.19	0.25	0.52		

On the three small adjacent basins UHL, BL, KR there were rainfall data from five gauges within the catchments and with the help of other stations isohyets have been drawn (Pivrnec & Bicik, 1992) for a large flood (N=5-50) caused by rainfall equal to the mean of annual maxima of 1-day rainfall totals. The C_{obs} (Table 2 in the column C_{obs} for Q_N) should therefore be reasonably correct. Two of the catchments (BL, KR) are part of the Kamenice catchment which at site Josefuv Dul has an area of 25.81 km^2. For this larger catchment the data set for coaxial correlation is available (CHMI, 1992). From 56 events the C_{obs} for those with causative rainfall over 80 mm (the mean of annual maxima of 1-day rainfall) are given below:

P[mm]	80-130	130-200	200-270	270-300	318	385
	15 events	8 events	0.73	0.67	0.51	0.70
	0.37-0.75	0.42-0.67	0.35			
	0.25	0.26				

UNIT HYDROGRAPHS

On four of the study catchments a detailed analysis and intercomparison of unit hydrographs (UH), dimensionless unit hydrographs and the effect of rainfall pattern on the responses has been performed. The results are presented in a schematic way in Figures 4, 5, 6 and 7. The parameters of UHs have been identified using the PICOMO program (Dooge & O'Kane, 1977). A dimensionless UH (Dooge, 1977) was obtained by plotting UHs in the coordinates t/t_L and $h.t_L$, where h are ordinates of UH [h^{-1}], t is time [h] and t_L is the lag of the catchment [h]. Under certain conditions different UHs on one catchment can plot into one dimensionless UH (as e.g. Figure 5). The question then is which of the responses should be taken as "the correct one", i.e. the catchment response which should be used for design purposes.

On the Sputka catchment (Figure 4) 27 events were chosen for the analysis (a detailed description is presented in Blazkova, 1992). In Figure 4 some characteristic examples are given (Nash model; parameters N and K). Three families of dimensionless UHs have been identified (Figure 4a); the B and C families are caused by spatially non-uniform rainfall. Family A has rainfall approximately uniform in space, but still the time-distribution can cause large differences. The catchment response is the middle UH of family A (Figure 4b) brought about by events of net volume P_e larger than 2 mm, uniformly distributed in time and with an initial flow in the range 0.5 to 1.0 m^3 s^{-1}. Large events tend to converge to this curve, e.g. the event with N=10 years (P_e=17.4 mm).

On the Tepla catchment all four UHs (Nash model) plot into one dimensionless response (Figure 5). The three sharper UHs have been identified as summer events with small P_e due to small C_{obs} (0.02-0.08). The lowest UH is of the above mentioned flood from the beginning of April just after the end of snowmelt. Because important peaks are caused by this type of situation the lowest hydrograph should be taken as the catchment response.

In the Jizera basin the UHs have a sharper shape (conceptual model channel and one linear reservoir; parameters T_{ch} and K_{1r}). At the VIL site (Figure 6) a certain dependence can be seen on net rainfall intensity P_e/D_e, where D_e is the duration of effective rain [h]. The A family contains large floods (Q_{100} and Q_{10-20}), the UHs of which have shorter lag. In the dimensionless plot the effect of D_e prevails. At site DSYT it is mainly the composition of flows from sub-basins which has effect on UHs. It normally rains more at the station DS than at VYS (Figure 3a) but in case of the two UHs of family A in Figure 7 the contribution from the upper part was very heavy and non-uniform.

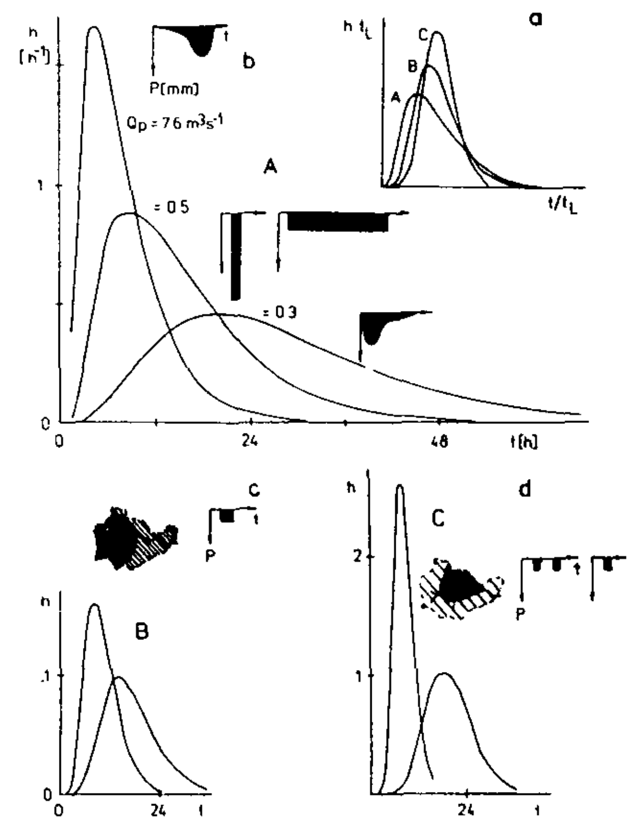

Figure 4 *The Sputka basin: schematic plot of the effect of rainfall pattern and initial runoff on the unit hydrograph identification; a - dimensionless unit hydrographs; b, c, d - unit hydrographs*

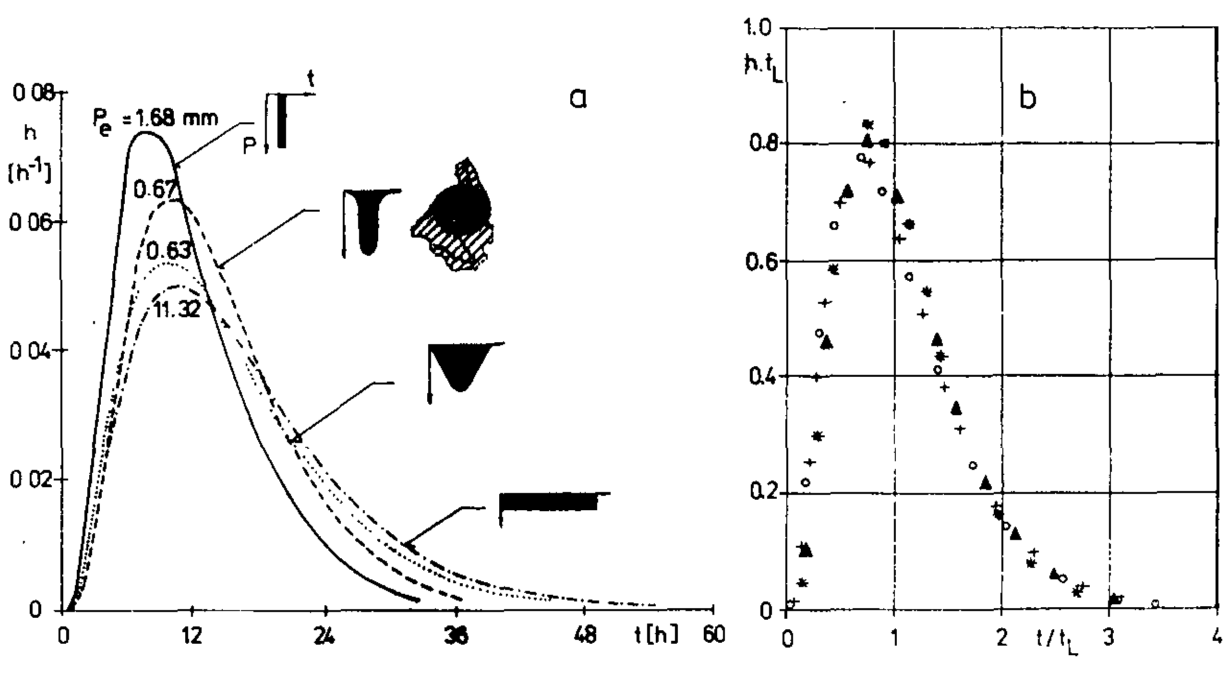

Figure 5 *The Tepla basin: schematic plot of the effect of rainfall pattern on the unit hydrograph identification; a - unit hydrographs; b - dimensionless unit hydrographs*

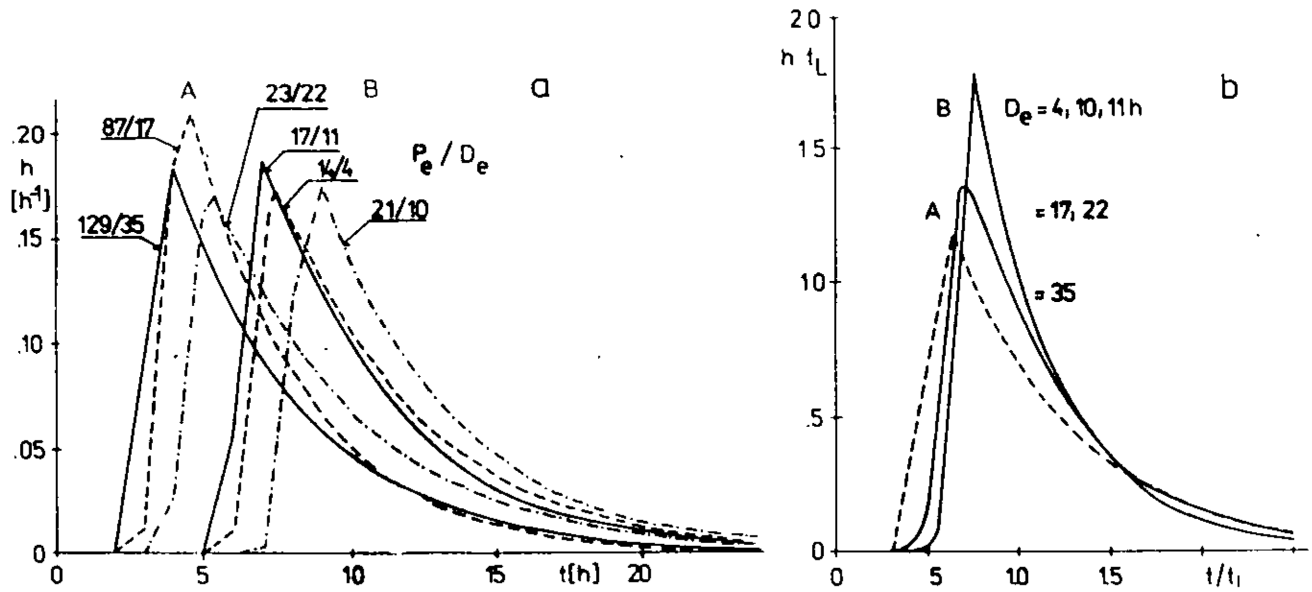

Figure 6 *The Jizera basin at site VIL; a - unit hydrographs with volumes [mm] and durations [h] of causative effective rainfall; b - dimensionless unit hydrographs with durations of effective rainfall*

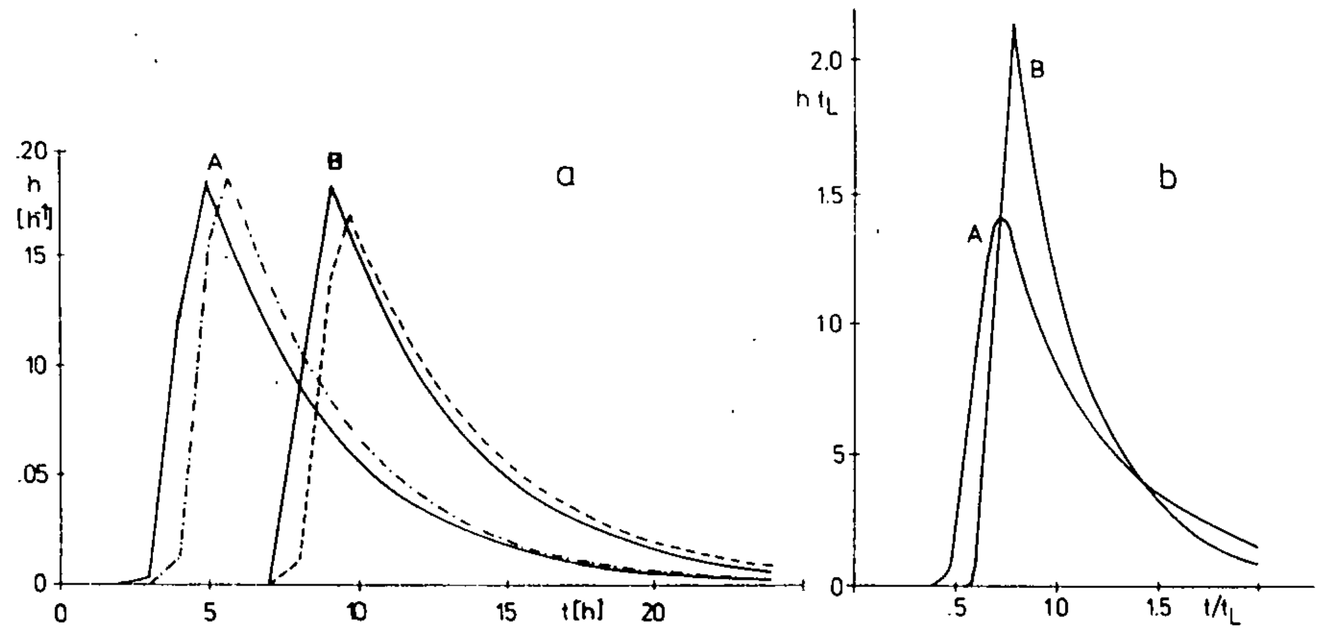

Figure 7 *The Jizera basin at site DSYT with the effect of runoff composition from sub-basins; A - rainfall non-uniform in time and heavier contribution from the upper part; B - uniform rainfall; a - unit hydrographs; b - dimensionless unit hydrographs*

IMPLICATIONS FOR FLOOD PREDICTION

For all the sites in Table 2 flood peaks with a return period of 100 years (Q_{100}) were computed using the catchment UH or the UH available, and the biggest C_{obs}. The modelled Q_{100} has been compared to Q_{100} (last column) determined by statistical methods and regionalization, or by analogy based on regionalisation (CHMI, 1992). In case of important differences the runoff coefficient has been calibrated by trial and error (C_{calib}) to get Q_{100}.

For the Upper Vltava and Sputka and Tepla basins the Nash model is the best one with the exception of Studena Vltava at site CKV, where also the parameters of channel and linear reservoir are given. In the Jizera Mountains, on the other hand, the channel and reservoir is by far the best, possibly with the exception of Mumlava at site JH. A third model, the convective diffusion equation, lies between the first two models and would be therefore the safest in regions where no calibrated UHs are available.

On the Tepla catchment the calibration of C failed due to the importance of snow in the basin. Both the performance of the sharpest response to summer rainfalls and of the response on the catchment saturated after snowmelt are shown. On such catchments the effect of snowmelt will have to be taken into account for design flood determination. On the other catchments the use of isolines of mean annual maxima of 1-day rainfall leads to reasonable predictions. The isolines were determined from long series so that the areal rainfall is not underestimated as on individual events with an insufficient number of rainfall stations.

COMPARISON WITH OTHER AREAS

On the Sputka (104 km^2) and Tepla (286 km^2) basins no relation of UH parameters to rainfall intensities has been found. The shortening of t_L and increase in peak within a family of UHs is dependent on the space-time distribution of rainfall and not on intensities as in the well-known example given by Minshall (1960) on a catchment of 0.109 km^2 (the causative rainfall was of the duration of about 15 minutes). On Minshall's larger catchment (1.174 km^2) the relation was less pronounced. On the Jizera basin at site VIL (146 km^2) a certain dependence on intensities exists (Figure 6a). It is interesting to compare the average intensities of effective rainfall of storms with longer duration. The largest events at VIL have P_e/D_e equal to 129/35 and 87/17 mm/h and the Minshall's data for the larger catchment have 100/29, 80/14 and 93/25 mm/h (runoff was not separated because of small percentage of baseflow and interflow).

The comparison of runoff coefficients with those given in Dunne (1978) is difficult due to the absence of detailed knowledge of runoff generation mechanisms for catchments in Bohemia. Dunne gives maximum runoff coefficients dependent on the basin area for Horton overland flow during large rainstorms in the southwestern US. On the catchments in the present study with those coefficients also large events were modelled. For example on the Sputka the C_{obs} for N=10 years was 0.14 and from Dunne's curve the C for 100 km^2 is about 0.17. On the small catchments in the Jizera Mountains the C_{obs} and even C_{calib} for Q_{100} would be close to the Dunne's curve but the decrease of C with the increasing area in the Jizera Mountains is much slower (Table 2).

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18. Spatial comparison of water quality in rivers

W. Symader

ABSTRACT

To provide a framework for future research the temporal behaviour of major ions and heavy metals in dissolved and particulate form were investigated in two field studies with twenty and thirty-one basins, respectively, between 1972 and 1977. The complex structure of the data sets provided the opportunity to compare average conditions of water quality, temporal behaviour patterns and basin characteristics for different groups of water quality variables. Considerable differences between the spatial distribution patterns of different sets of variables provided further information. As the basins were heterogenous in land use and bedrock, it was possible to assess the influence of basin characteristics on water quality behaviour, although many of the characteristics were highly intercorrelated.

INTRODUCTION

The vast number of case studies in catchment hydrology contain information that is difficult to handle. Because of differing theoretical concepts, approaches, sampling strategies, scale effects etc, contradictory results cannot be exclusively explained in terms of different hydrological environments. Furthermore it is not easy to assess, whether the results obtained can be generalized, are of local importance or are caused by special circumstances. The problem of evaluating case studies becomes more evident when a strong need exists to compare results, as it is the case of the Experimental and Representative Basin Network.

However, there is probably no general answer to the question of how river basins are to be compared, because much depends on the objectives of the investigation and the structure of the data set.

In order to obtain a first understanding of temporal and spatial variations of major ions and heavy metals in flowing waters which should provide a base for subsequent projects, two extended field studies were carried out in the northern Eifel mountains, the adjacent loess zone, and the Lower Rhine area from 1972 to 1978 (Symader, 1976, 1984). Additional investigations were carried out by Rump (1976) who studied pesticides, Krutz (1979) who worked on cyanides and Thomas (1978) who investigated heavy metals in channel sediments. Although the amount of data collected was hardly sufficient to answer all questions, as it was found out later, the complex structure of the sampling programmes offered several possibilities for comparison.

THE DATA SETS

In the first study chemical analyses of biweekly samples were restricted to the dissolved ions PO_4, NO_3, NH_4, Na, K, Ca, Cl, SO_4. Additional variables were electric conductivity, O_2, pH, suspended particle concentration, turbidity at 420 nm, water and air temperature, discharge and daily precipitation were measured. Twenty catchments were investigated.

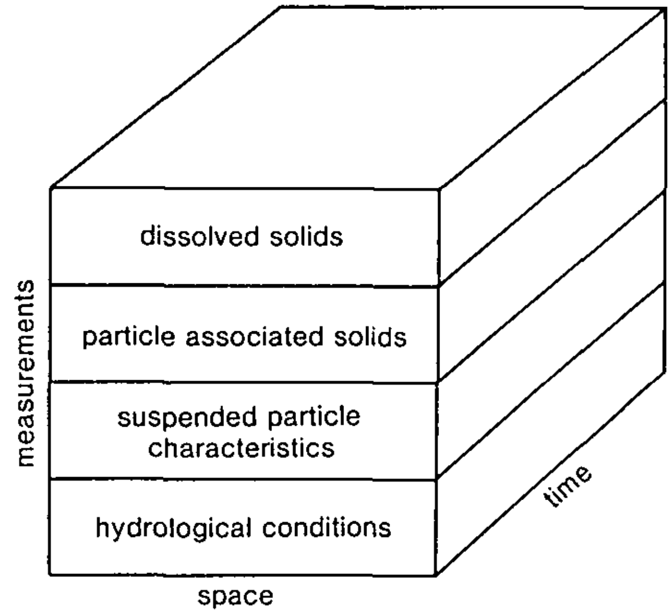

Figure 1 *Three-dimensional structure of the data sets*

In the second study the heavy metals Zn, Fe, Mn, Cu, Pb, Cd, Ni, Cr, and Co, were also included in the programme although analyses of NO_3, NH_4, Cl and SO_4, were cancelled. All heavy metals and major ions were investigated, both in dissolved and particle associated conditions. Suspended particles were described by concentration, turbidity at 420 nm, loss on ignition and the coefficients of a power function between turbidity and wave length, which gave a rough idea of the median particle size.

The outstanding characteristic of both data sets is their complex structure. This structure can be described by a three dimensional matrix with the two dimensions time and space (Figure 1). The third dimension contains the variables from the measurements, which can be classified into several groups. Time and space are both represented by nearly the same number of measurements, which means that there is no dominance of one dimension over the other. The measuring programme of the first study dealt with the two aspects of dissolved solids and water cycle. The second study covered four aspects, namely dissolved nutrients and heavy metals, suspended particle characteristics, particle associated nutrients and heavy metals, and the water cycle.

Thus the possibilities for comparisons included temporal aspects of individual basins, such as differences between the two studies or among different seasons within the year, as well as spatial aspects, such as intercomparisons of basins concerning typical or average situations and conditions. Furthermore temporal and spatial aspects can be combined as it is the case in assessments of behaviour patterns among individual basins. The multivariate sampling programmes allow both a restriction to one or a few solutes that are relevant for environmental problems, but also offer the possibility of considering all variables for a wider scope. Furthermore, comparisons among the individual subsystems dissolved solids, particle associated solids, and the transporting media flowing water and suspended particles can be carried out.

AREA UNDER INVESTIGATION

The northern Eifel mountains were chosen for the two studies, because of their variability in bedrock and land use. They consist of Devonian schists, quarzites, shales and greywackes, and are covered by woods and grassland up to 75%. The density of settlements is low, but increases in the valleys. The embedded areas of Devonian reef limestones provided better opportunities for agriculture and consequently show a number of small rural settlements. Triassic hills with Mesozoic sandstones and limestones form a triangle at the northern border of the mountains. The sandstones are partly plumbiferous and had been centres for ancient mining and settlements. Beside lead, silver zinc and cobalt can be found. A second area with ore deposits bearing zinc and lead, accompanied by iron, cadmium, nickel and cobalt is situated in the western part of the Eifel. It was the starting point for the early industrialization of this region and is now part of the industrial zone of Aachen-Eschweiler-Stolberg. Detailed descriptions of the ore deposits are given by Gussone (1961). Their influence on soils and channel deposits were investigated by Kulms & Friedrich (1970).

Minor tourist and industrial activity can be found where the Eifel valleys enter the adjacent loess area. The loess area itself is intensively cultivated. Clusters of rural settlements and smaller cities have a strong impact on water quality, which finds its maximum around the cities Neuß and Düsseldorf near the Rhine River.

The area under investigation includes natural headwater catchments, regions with extensive and intensive agriculture, and centres of settlements and industry. This variety of hydrological environments was chosen because the authors intended to transfer the obtained results to other catchments where no measurements could be made.

Figure 2 shows the four main groups of basins according to different landscape patterns, which are labelled Devonian mountains, Triassic hills, loess area, and dominance of industry and settlement. The 31 gauging stations of the second study are shown in Figure 3.

RESULTS

Although temporal comparisons have been made within the sampling periods and between the two studies, the main task was the assessment of the influence of different hydrologic environments on transport phenomena. The temporal comparisons resulted in a better understanding of the significance of the runoff generation process (Symader, 1985, 1988) and revealed the starting point of river acidification (Symader, 1989) in the northern Eifel mountain. The spatial comparisons offered more possibilities and consisted of several steps.

Using a hierarchical grouping analysis (Ward's algorithm) mean concentrations of nutrients and heavy metals were clustered into groups and compared with characteristics of the basins. The results were trivial and met the expectations: mean concentrations were low in the headwater catchments and increased from the mountainous areas to the foothills and the flatland according to increasing catchment size and human activities. But because of high spatial intercorrelation it could not be determined if population density, drainage area, bedrock or a combined effect was responsible for this spatial trend. The same held true for the heavy metals except for some deviations related to the special conditions of ore bearing deposits.

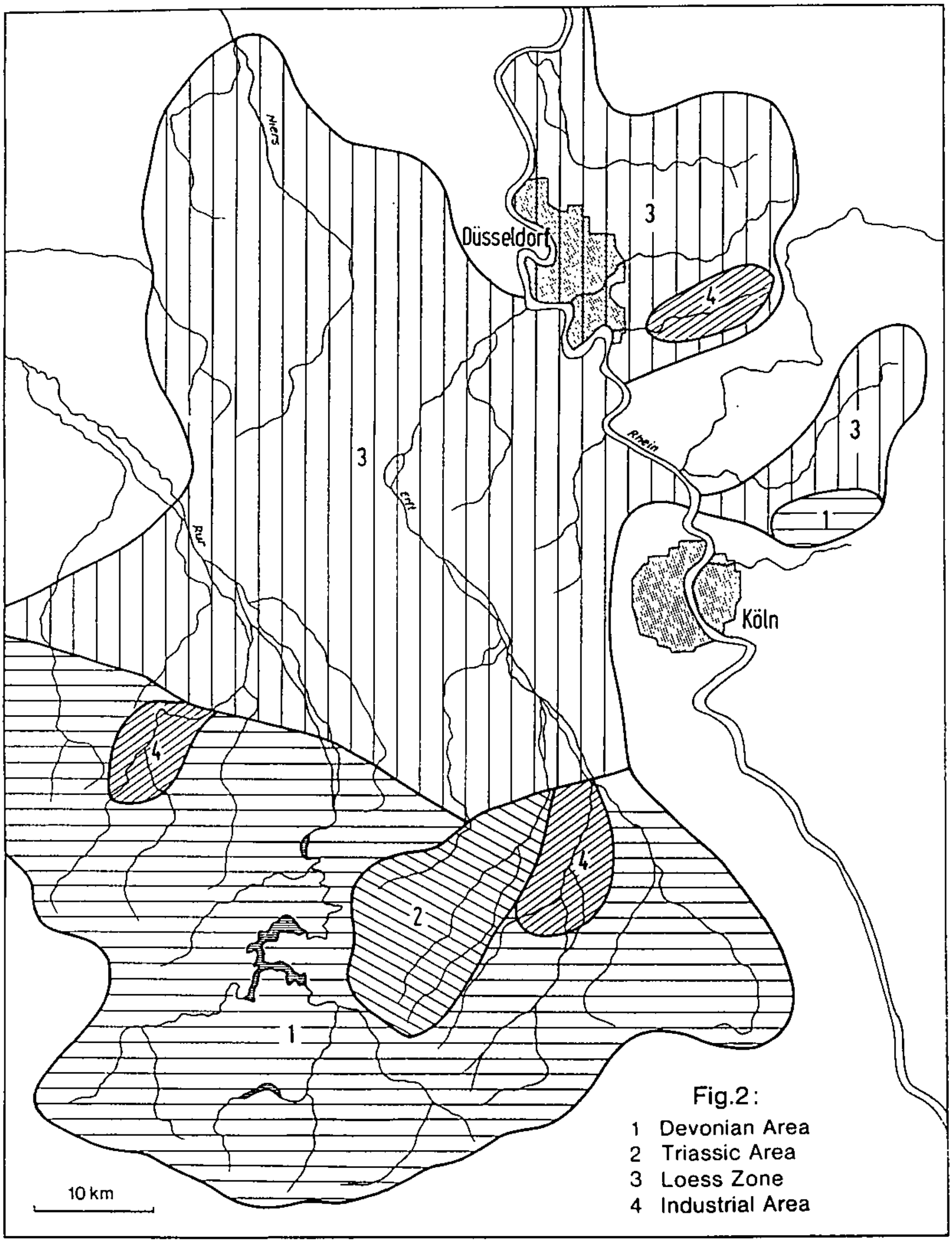

Figure 2 ***Study area showing the four landscape units used***

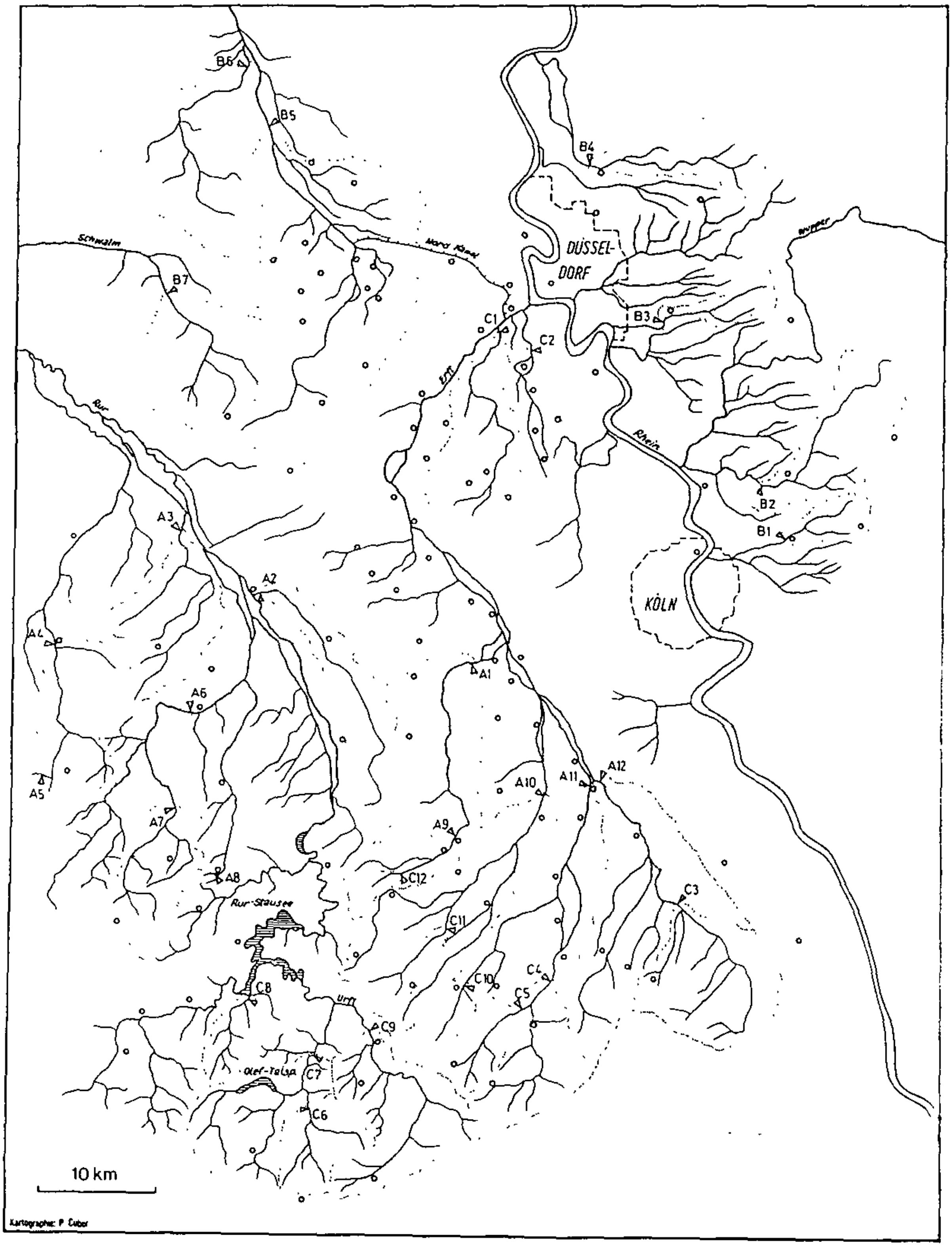

Figure 3 *Locations of the 31 streamflow gauging stations used in the second study*

In a second grouping analysis an algorithm was used that calculated the relations between all variables (Symader & Thomas, 1978). Although this algorithm put the emphasis on the chemical profile, and did not consider general spatial variations in mean concentrations, it surprisingly produced the same spatial patterns as the first procedure. This could only mean that an increasing degree of pollution coincides with a characteristic shift in the elemental composition, i.e. that degree and type of pollution display similar spatial patterns.

Both analyses were repeated with particles of associated solids and heavy metals in channel sediments, resulting in eight individual maps of distribution patterns in total. Striking differences between the distribution patterns of dissolved solids, suspended particle associated and channel sediment associated solids cast serious doubts on the assumption that the assessment of heavy metal concentrations in channel sediments can give more than a rough idea about river pollution. More important are the composition of suspended particles and channel sediment material, or the local sources of heavy metals, such as bedrock and different types of waste water.

An additional comparison between suspended particle characteristics, basin characteristics and differences between the spatial distribution patterns of heavy metals in dissolved and particulate conditions was carried out, but was not very successful. The problem is still unsolved of how the composition and properties of suspended particles can be quantified. Particle concentration, grain size distribution, organic carbon and density, which all can be measured without too much effort, are not sufficient.

In a third analysis the basin characteristics were compared with temporal structures. For each catchment a matrix of intercorrelation was calculated for all water quality variables and for dissolved solids only. Using the major ions from the first study it was discovered that basins could be classified into groups of quite different behaviour that were labelled natural basins, basins dominated by pasture, agricultural basins with considerable and severe erodibility, basins with rivers that are dominated by domestic sewage and faeces, and basins with rivers dominated by waste waters from minor industries.

While the first two analyses classified the basins according to degree and type of pollution, this grouping revealed the source of pollution. Comparisons with basin characteristics showed that different groups of behaviour could be associated with different landscape units. This relationship was quantified using a multivariate discriminant analysis. Two misclassifications showed how difficult it is to describe a basin properly. One catchment with low concentrations of most ions was supposed to belong to the group "domestic sewage" because of a large camping site upstream. Another catchment with woods, small patches of bushland, and some scattered areas of pasture and arable land showed the general characteristics of severe soil erosion except for very high concentrations of suspended particles. The first explanation was an excess of fertilizers and the application of manure during rain events, which was observed several times. Later then, when the data base of the second study was available, it was found out that this behaviour was due to a combined effect of agricultural practices and soil acidification.

A comparison of the results of the three analyses, i.e. degree, type and source of pollution, gave an additional insight into the temporal-spatial interdependencies. The classification according to the source of pollution did not show the spatial trend from headwater catchments of the mountains to the loess zone that was observed in the first two analyses. Besides, dealing with basins of one group only, the spatial intercorrelation of basin characteristics that was responsible for the problems in evaluating the spatial trend decreased considerably. The spatial intercorrelations were caused by variations of basin characteristics between different landscape units. For each group a different combination of basin characteristics was responsible for the water quality of the river. In a rural basin water quality is controlled by farming practises and erodibility of soils. The influence of settlements is of minor importance as long as a certain threshold is not exceeded. In that case the basin is not a rural basin any more, but belongs to a different group. This non linear relationship between water quality characteristics and varying combinations of significant basin characteristics should not be understood as a result from a continuous temporal or spatial process. It only reflects the discontinuity of highly intercorrelated landscape characteristics, but it can be used to design proper sampling strategies for well defined objectives.

DISCUSSION

What do these results mean to questions of basin comparison? Comparisons will always show differences. So it is the evaluation of these differences that has to be discussed. The starting point for doing this must be the purpose of the comparison, because the purpose sets most of the boundary conditions for the following methodologic procedures. This statement sounds trivial, but it is a fundamental difference, if comparisons are used as a method of "data snooping" to get new ideas, in which case everything is allowed that produces results, or if questions are to be answered.

One of the objectives of the two studies presented in this paper was to establish a framework for future research. The central question for the two studies, and all following investigations, was whether the results obtained from a study can be generalized, are of local importance, or depend on special circumstances. From this question it follows that the framework should cover a wide field and show as many angles as possible. That is why such aspects as data structure, sampling programmes and basin characteristics became so important. As no statistical testing or decision-making was involved, statistical procedures such as cluster, regression or discriminant analysis were only used to handle the complex set of data.

The outstanding feature of the data sets was their temporal and spatial dimensions combined with a multivariate approach of chemical analyses, and sufficient samples to get a rough idea of the relationship between basin characteristics and those dominant processes that control the water quality behaviour. Except for some headwater catchments all basins were heterogenous in land use and often in bedrock as well. The advantage of such a choice is obvious. Although many basin characteristics are often intercorrelated in space, their influence on water quality can be evaluated by statistical methods, because varying proportions of different land use and bedrock occurred in many combinations. There is a hierarchy of ranks among the basin characteristics. However, as landscapes can change non continuously, this hierarchy is not constant. What is significant in one type of landscape, becomes meaningless in another. This effect is similar to the change of priorities of processes in basins of different scales (Kirkby, 1988) and leads to similar problems.

It can be argued that this is rather trivial, because it has never been doubted that the hydrologic environment of a basin controls many of the processes in the rivers. However, this fact and its consequences are too often neglected. Scientists tend to generalize their results and there is sometimes a considerable debate that goes on for years, which factor or process is the dominant or most important one. In the 1960s and early 1970s German politicians wanted to know if it were detergents from waste waters, or fertilizers from soil erosion that caused the eutrophication of surface waters. A question which is put that way can never be answered.

A similar discussion on runoff generation processes has continued for a decade now.

The comparisons between different sets of water quality variables showed that average concentrations and temporal behaviour of dissolved solids are controlled by different basin characteristics. Furthermore there were considerable spatial differences between different subsets of variables such as major ions and heavy metals, or such as dissolved solids, suspended particle associated solids or solids in channel sediments. Again, the comparisons of different spatial distribution patterns helped in discovering additional hidden factors.

Since 1988 detailed investigations on the catchment response to rainfall events have been carried out in three catchments of the southern Eifel mountains and the Hunsrück mountains near Trier. The experience of the relationships between hydrological processes and basin characteristics gained from the two studies presented in this paper was the only reliable basis for assessing how far the results can be generalized or transferred to other catchments.

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19. Methods of catchment characterisation by means of basin parameters (assisted by GIS) - empirical report from Switzerland

R. Breinlinger, H. Düster & R. Weingartner

ABSTRACT

After decades of process orientated basin research, when regional investigation methods were neglected, regionalisation in hydrology - set against a background of increased practical demand - has increased greatly in importance. The determination of thematically and spatially comprehensive basin parameters that are hydrologically relevant has therefore become a high priority. This paper describes two research projects, firstly a spatial, hydrological data base for all of Switzerland, and secondly a process orientated determination of basin parameters for the spatial extrapolation of rare flood discharges.

INTRODUCTION

Knowledge of hydrological conditions is fundamentally important not only for planning and dimensioning in water-resources management and environment protection, but also for yes-no questions in politics. Although its hydrological and climatological networks are comparatively dense, Switzerland is faced with considerable data gaps - a fact emphasising the need of regionalisation methods for the assessment of hydrological characteristics for basins lacking direct measurement. These methods are mostly based on both a catchment characterisation by means of basin parameters, and modelling of the correlations between those parameters and the hydrological factors of concern.

Intensive process research in small basins spanning years and decades, gave way to extensive regional research projects during the 1980s and at the outset of the 1990s, such as "Assessment of discharges in rivers and streams at locations with no direct measurement", "Hydrological Atlas of Switzerland" and "Design flood" (to name the most important). In due course, a great need became evident for thematically embracing, spatially resolved catchment characteristics as a basis for a successful use of regionalisation methods. This development was given a boost by the availability of geographical information systems (GIS). The present report describes the experience gained in defining basin characteristics in Switzerland and discusses the methods of regionalisation resulting from these characteristics. The emphasis, however, is put on those methods that, above all, permit studies at regional to national scale.

STRATEGIES TO YIELD CATCHMENT CHARACTERISTICS

Not only the yield but also the quality of catchment characteristics is influenced by various factors such as the hydrological statement to be achieved, observation scale, required spatial data resolution, data available, hard- and software etc. From the methodical point of view, three procedures are in principle to be distinguished (Table 1). Whereas for spatially orientated methods spatial units are assumed above all (usually hydrological basins), process orientated methods do have their roots in catchment characteristics relevant to the process under consideration. To quote as a first illustration a spatially orientated method is presented. Its great flexibility in parameter assessment proves convincing and allows further parameters to be easily computed and added at a later time, thus meeting diverse hydrological problems. Its spatial fixation to given units, however, may be impeding. Catchment characteristics being given as mean values, any direct locational consideration is precluded.

Table 1 *Methodological approaches*

SPATIALLY ORIENTED METHOD ←	→	PROCESS ORIENTED METHOD
A	B	C
1) Delimitation of hydrological basins (assisted/not assisted by GIS) 2) Assessment of relevant parameters	1) Delimitation of process relevant areas (GIS assisted) 2) Assessment of parameters relevant for considered process	1) Assessment of relevant parameters (depending on process) 2) Delimitation of so-called units of smallest geometry in common and yield of parameters by means of GIS
APPLICATION - Use in models - Classification	APPLICATION - Use in models	APPLICATION - Classification - Models (water balance)
[+] • High flexibility, ready for diverse questions • Rather poor data set	[+] • Spatial width linked with high spatial parameter resolution (limitation to the essential)	[+] • Close to process • High spatial resolution • Use of detailed models • Homogeneous areas
[—] • Mainly spatial fixation • Parameters available as mean values	[—] • Areas being dependent on target designation	[—] • Correlations of spatial units not apparent • Units dependent on selected parameters • Detailed models required • Large data set
Example: Hydrological Atlas of Switzerland	Example: Estimation of design flood	Example: MAB-Analysis Berchtesgaden

The second method is to be settled within the transition of the spatially to the process orientated procedure. Investigation is limited to those catchment areas in which the processes of concern actually occur, thus being defined as contributing areas in the flood scope. Although a spatial averaging of the characteristics is inevitable, the parameters gain physical significance both by being close-to-processes as well as the considerably smaller areas compared to the first method.

The way to the so-called smallest geometry in common - virtually the unit area being homogeneous as to the parameters selected and thus to the process under consideration - is smoothed by the overlay capabilities of the Geographical Information System. A high spatial resolution is inferred from this method, permitting a locational consideration assuming however - as a limiting factor to the application of this method - all of the characteristics relevant to the process are in fact known. As with the other methods, data at the highest possible resolution are required. Whereas the first two methods are based on hydrological catchments, this method embraces spatial units, therefore the correlations are not given and have to be determined by suitable procedures (e.g., by means of cascading).

SPATIALLY ORIENTATED YIELD OF CATCHMENT CHARACTERISTICS TO SERVE AS A BASIS FOR A SWISS HYDROLOGICAL DATABASE

In the scope of work on the "Hydrological Atlas of Switzerland", the Hydrology Group of the Geographical Institute of Bern University set out to provide catchment characteristics for the whole of Switzerland (medium to small scale). For this purpose, a spatial system of catchments comprising three levels was developed (Figure 1). Large catchments (river basins) usually covering an area of multiple 1000 km^2 are the top level. The water balance basins including catchments of 100 to 150 km^2, are a result of subdividing the river basins. Small catchments (30 to 50 km^2) make up the lowest level of the spatial system. By means of aggregation or disaggregation, a direct comparison of catchments within one level, and a linking of the catchments one below the other in all three levels is possible, thus permitting different hydrological statements. On the level of large catchments and water balance basins the hydrological data analysis (water balance, time series) is predominant. Due to the large spatial variability of catchment characteristics, their yield is limited to the level of the rather small basins. However, these basins being poorly provided with direct measurement of discharge, in particular, a hydrological assessment of catchment characteristics has to be assumed.

DELIMITATION OF SMALL CATCHMENTS

The determination of small catchments was carried out by subdividing the water balance basins[1]. To derive spatially representative parameters, the division into small catchments aimed at the extraction of the most homogeneous catchments possible. Catchment surface was the first criterion of division. An area ranging 30 to 50 km^2 was assumed as the standard, because the basin characteristics in relevant catchments are subject to rather small fluctuations on the one hand, and the number of catchments is easily comprehensible on the other.

Since many characteristics - such as land use for example - are dependent on altitude, the elevation distribution was also taken into account for defining the boundaries of the small catchments.

[1]The water balance basins strongly follow the existing hydrometric networks (cf. Schädler and Weingartner 1992)

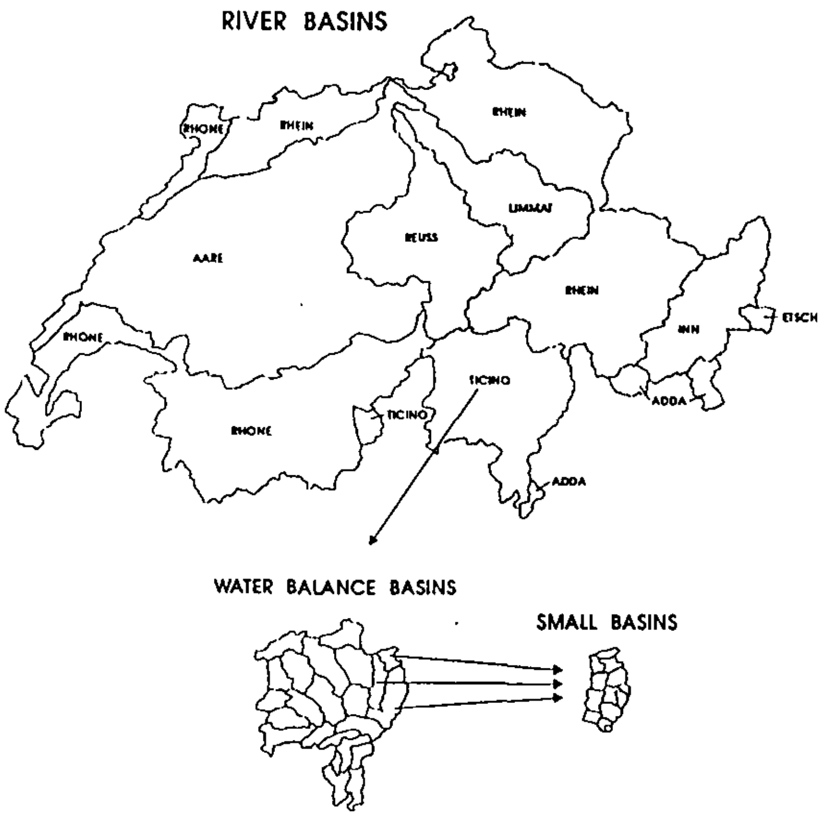

Figure 1 *Large river basins, water balance basins and small basins of the "Hydrological Atlas of Switzerland"*

For the deep alpine valleys of the Rhine and the Rhone, a deviation from a rigid selection of hydrological catchments was necessary. Here, the valley sides were distinguished from the valley floor, thus avoiding two totally different hydrological units (such as valley floor and high mountain ridges) to be mixed in the same catchment. Open catchments with several outlets resulted. Around large lakes and in areas where the Rhine and the Doubs shape national boundaries, no hydrological catchments in the proper sense could be distinguished either. Yet, to allow hydrological statements for such instances, a most representative possible catchment was considered within such regions and relevant characteristics were transferred to the whole area.

The spatial division of Switzerland was carried out at an operation scale of 1:200000 and yielded approximately 1050 catchments a median area of 37 km^2. The smallest catchment covers 7 km^2, the largest 195 km^2. The catchment boundaries were digitised and converted as plotting geometry into a Geographical Information System (GIS ARC/INFO).

SELECTION AND YIELD OF CATCHMENT CHARACTERISTICS

Within the scope of a preliminary study, an evaluation was made of the basin parameters that are relevant to hydrological investigations, models and regionalisation methods. A final selection had to consider the characteristics that could be obtained from the available data. For the whole of Switzerland, the following fundamentals were at hand: Digital elevation model (altitude, slope, exposition; lateral length of grid 250 m), the land use statistics (lateral length 100 m) in grid form, as well as the river network at a scale 1:200000 in vectorial form, the soil suitability map 1:200000 and the geotechnical map 1:200000, the latter three having been made available by the scanning of current maps. Since the commonly applied GIS ARC/INFO operates vectorially, part of the data, however, initially had been transmitted as raster data and had to be converted to vectorial form.

Using the overlay and statistics capabilities of the GIS, it was then possible to calculate the characteristics for each catchment, mainly as spatial mean values (e.g., mean slope) or percentile values (e.g., forested portion). The 37 invariate parameters determined are listed in Table 2 and published in the "Hydrological Atlas of Switzerland" by means of a map (Breinlinger, Gamma & Weingartner, 1992). Thus they represent the basis for a spatial hydrological data bank of Switzerland. This database is most likely to be expanded by mainly variate characteristics. For an estimation of hydrological parameters, especially runoff characteristics, the database will be connected with suitable hydrological models thus very easily putting to good use hydrological statements relevant to planning for the whole of Switzerland.

A possible application of this database is illustrated by a classification of small basins, a classification that is to reveal a possible similarity of the basins considering their invariate parameters relevant to discharge and consequently their similar hydrological behaviour.

CLASSIFICATION OF SMALL BASINS IN SWITZERLAND

For a multivariate basin classification by means of catchment characteristics the TWINSPAN method (two way indicator species analysis) was applied (Hill *et al.*, 1975). The methodology is based on an ordination procedure likely to be compared to a principal component analysis - the reciprocal averaging - as well as to a splitting square with the ordination axis of the investigated objects (small basins). This process of splitting is to be repeated within the resulting classes and ends theoretically when the number of basins is equalised. A dendrogram can be established capturing the characteristics (species) most likely to reproduce the respective class splittings optimally (indicator species).

The classification depends on the hydrological parameters in question acknowledging particular combinations of characteristics to be relevant. The four classifications, either planned or partly realised, are due to reveal the similarity of small basins, mainly in the scope of flood, mean water and low water. The characteristics selected for the flood variant can be allocated to either of the three flood relevant processes storage, discharge development and concentration.

Table 2 *Part of 37 catchment characteristics published in Hydrological Atlas of Switzerland*

			Altitude				Slope		Surface and Soil				
No	F_N [km²]	P [km]	mH [m]	H_{max} [m]	H_{min} [m]	I_w [°]	I_3 [%]	I_{15} [%]	F_{vgl} [%]	F_{vsg} [%]	F_{Bo} [%]	F_w [%]	WSV [mm]
60073	61.6	37.5	1616	2950	350	26.6	0.3	91.8	0.0	0.7	83.4	48.5	16.2
60081	16.4	19.3	1923	2950	550	26.5	0.6	88.7	0.7	0.0	57.6	39.1	15.7
60082	51.8	29.2	1669	3050	550	28.2	0.3	91.2	0.4	1.3	75.4	30.9	14.1
60083	27.9	22.5	1789	2650	550	28.6	0.3	91.4	0.0	0.0	59.2	25.4	18.5
60084	42.1	32.3	1330	2650	345	30.6	2.1	89.4	0.0	0.5	77.8	46.0	16.9
60085	59.9	32.5	1356	2550	350	28.6	1.9	88.8	0.0	0.6	83.9	43.7	16.2
60086	30.5	21.7	1474	2450	350	26.8	0.1	93.1	0.0	0.1	93.4	51.9	15.3
60087	32.9	26.0	771	2150	250	23.4	6.8	77.7	0.0	1.8	96.7	62.2	22.3
60091	16.1	17.8	1294	2250	250	24.8	0.2	87.7	0.0	0.0	100.0	73.6	20.3
60092	45.0	32.6	1302	2150	250	25.3	0.4	88.5	0.0	0.6	98.3	47.8	16.5
60093	54.8	34.2	772	2350	250	19.6	17.9	69.5	0.0	5.7	86.4	46.6	24.1
60094	34.3	28.0	767	2350	150	17.8	30.1	62.3	0.0	3.8	95.8	40.1	24.3
60101	41.1	36.3	562	1950	150	15.6	33.7	54.0	0.0	2.8	99.0	40.2	33.4
60102[2)]	31.5	-.-	1104	1950	150	26.6	0.0	91.4	0.0	0.2	100.0	73.6	17.7
60111	24.1	21.5	1899	2850	950	32.2	0.2	93.5	0.0	0.0	68.1	15.2	10.8
	22.7	21.5	1766	2850	950	30.3	0.0	94.1	0.0	0.4	77.3	11.8	12.7
		24.4	1593	2750	750	28.4	0.2	91.1	0.0	0.7	83.4	20.8	14.3
			1722	2750	750	30.9	0.2	93.1	0.0	0.1	76.8	17.3	13.6
					650	29.6	0.1	93.3	0.0	0.1	82.0	20.6	16.9
						29.8	0.7	90.6	0.0	0.5	99.2	31.4	14.1
							0.7	91.7	0.0	0.6	94.3	45.9	16.9
									0.3	0.0	70.1	8.2	12.4
										0.4	75.0	24.7	14.9
												12.9	17.3
												8.6	15.2
													14.7

Key

No	Basin number	I_3	Surface <3°
F_N	Basin area (horizontal)	I_{15}	Surface >15°
P	Perimeter	F_{vgl}	Glaciers
mH	Mean altitude (weighted by area)	F_{vsg}	Impervious
H_{max}	Max altitude	F_{Bo}	Soil
H_{min}	Min altitude	F_W	Forested
I_W	Mean slope	WSV	Mean water retention capacity of soil

A first complete TWINSPAN classification covering 16 classes was achieved by means of a variant, including all basin parameters computed (Gamma, 1992; Figure 2). The classes best reproduce the natural units of Switzerland. By means of an optimisation assisted by discriminant functions, the range of variation of parameters within each class can be minimised thus increasing the significance of the classes. Multivariate plotting of the catchments by means of ANDREWS curves could reveal the existence of a number of outliers that presumably interfere with both the proper classification as well as the optimisation based on discriminant functions.

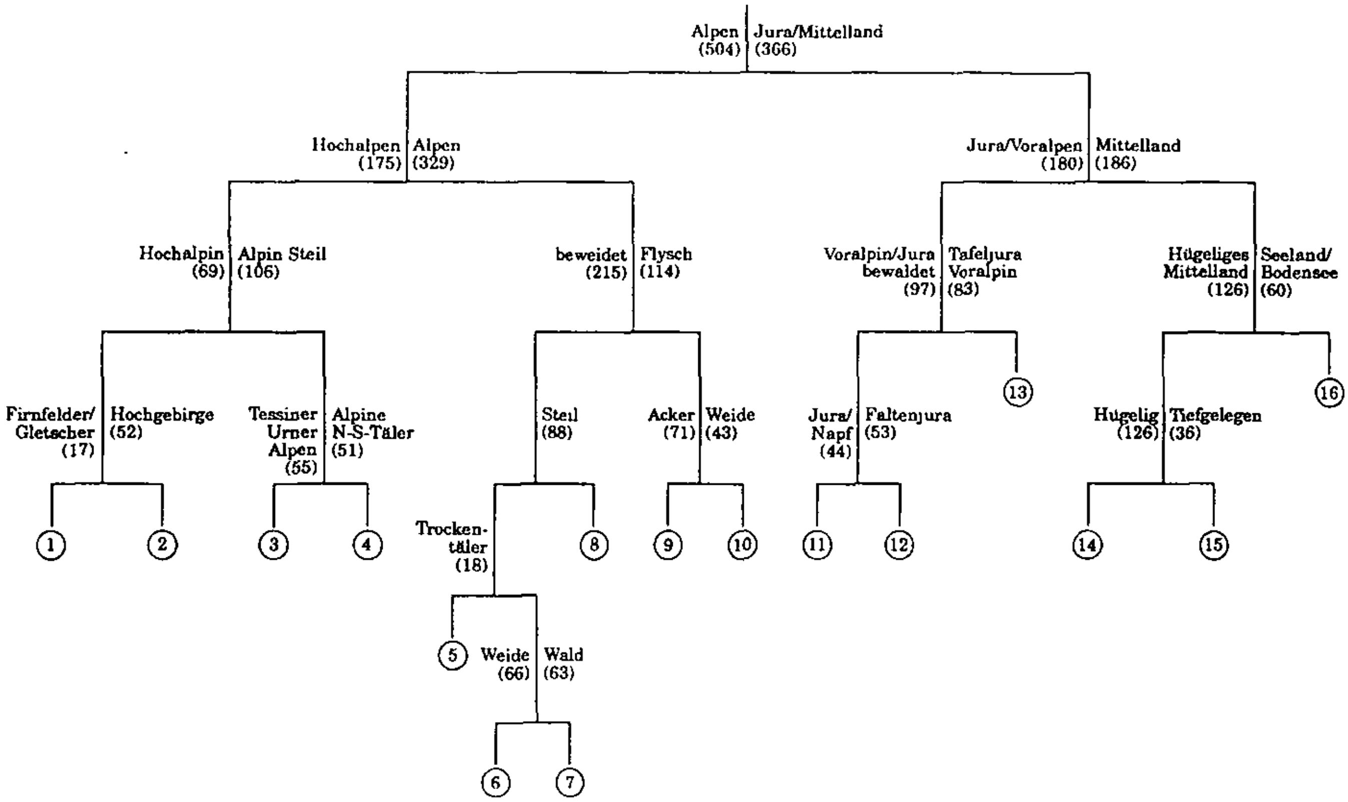

Figure 2 *Dendrogram of TWINSPAN classification, based on all computed catchment parameters*

This work is not yet completed and no definite classification of small basins in Switzerland can yet be presented. Not only an adequate hydrological interpretation but the practical usefulness of the classification is focused on. Thus the outcome of classification will also help embrace questions of the spatial representation of hydrological basins on investigation.

YIELD OF CATCHMENT CHARACTERISTICS FOR THE ESTIMATE OF FLOOD DISCHARGE (SPATIAL TO PROCESS ORIENTATED METHOD)

Past experience has proved that the application of conventional catchment characteristics for flood estimation has rarely imparted satisfactory results. The apparent uncertainties have their roots in the fact that the deduced catchment parameters make poor allowances for the processes concerned and are far too much spatially averaged. However, to investigate the spatial variability of flood flows, the application of basin parameters as characterising factors cannot be abandoned. Subsequently, process orientated catchment characteristics shall therefore be derived to allow an estimation of mean annual flood (HQ_2) on the one hand and infrequent floods (HQ_x, $x = 50$ years) on the other.

CATCHMENT VS CONTRIBUTING AREAS

The principle question arises of how to spatially define the catchment for the flood event, previous investigations having identified the relevant flood basin with the hydrological basin. A parameterisation of the catchment characteristics on this level occurred regardless of whether the areas concerned were hydraulically involved in the flood process. As various investigations showed (Betson & Marius, 1969, Hewlett & Nutter, 1970), only part of the hydrological basin is flood contributing (cf. Figure 3). It is these contributing areas that are given hydraulic access to the receiving water, the remaining area being irrelevant to the flood event. This fact is likely to be the cause of inadequate results in the parameterisation of catchments.

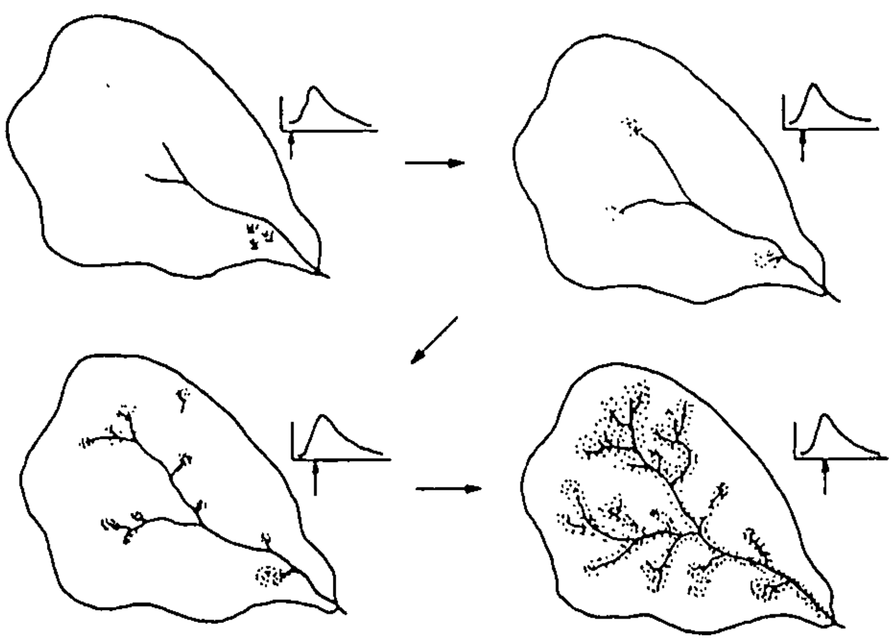

Figure 3 *Temporal variation of contributing areas during heavy rain (Hewlett & Nutter, 1970)*

The extent of the contributing areas greatly depends on both duration and return period of a flood. Poor knowledge exists nowadays as to the spatial expanse of contributing areas. According to Kölla (1986), areas close to channel within a distance up to 80 m can be considered as contributing areas for a mean flood in Switzerland. For the future, a more precise modelling of the expanse of such contributing areas is aimed at by field studies.

Subsequently, the actual contributing area represents the parameterising level for the derivation of flood relevant basin characteristics. To yield these areas, the total of perennial and episodical channels within the catchments on investigation was digitised at a scale 1:25 000. These digital data permit a 80 m buffer enveloping the channels to be generated by means of a GIS.

SELECTION AND YIELD OF CATCHMENT CHARACTERISTICS

To describe the process of flood discharge by catchment characteristics, this process is to be subdivided into the subprocesses involved. They are shown in Table 3, as well as the basin parameters that describe the subprocess and that are - the available data considered - to be deduced by means of GIS.

Table 3 *Subprocesses within flood process*

Process	Influenced by:
Precipitation	Depth of precipitation Spatial variation of precipitation Character of precipitation
Flow development	Vegetation Evaporation Soil conditions Contributing areas
Flow concentrations	Slope conditions Length of the river network

Precipitation represents the input value of the flood discharge process. It is rare that floods occur without any precipitation. A parameterising of precipitation as catchment characteristics, however, seems rather problematical. Due to a statistical updating of precipitation gauging series, the temporal succession of precipitation events, and with it the ultimate link with regard to the flood discharge process, is greatly impaired. Opinions therefore diverge as to the identification of both precipitation amount and duration leading to a flood at a specific frequency. Thus it is often assumed that the return period of flood equals the return period of the generating precipitation, an assumption which is rather unrealistic (Weingartner, 1989). To escape this problem, the decisive precipitation duration defined by Kölla (1986) is used as parameter, regarded as the period of time between precipitation and flood flow within the relevant basin. For each soil class a mean soil-moisture deficit is required that has to be made up by precipitation previous to flow developing from rain. Linked up with heavy rains regionalised for the whole of Switzerland (Geiger, Röthlisberger, Stehli & Zeller, 1992), it is possible to quantify precipitation as catchment characteristics.

Within a catchment, both vegetation cover and soil conditions, as well as the influence of lakes on the flow development of rivers, are decisive factors for the capacity of temporal retention of precipitation. The vegetation cover of the contributing areas is described through their land use, thus distinguishing forests, meadows and pastures, arable land and sealed urban areas. The whole of the latter is added to the contributing areas, the total of their precipitation input being supplied into the receiving waters by the sewerage network. The influence of lakes on flood discharge depends considerably on the location of the lake within the flood basin, or the fraction of the basin draining into the lake, as well as the extent of the lake. It is possible to shape this information from digital terrain models by means of GIS, so that not only the occurrence of lakes but their systematic influence on the flood discharge process can be considered. As indicators for soil retention, both depth and storage capacity, as well as soil permeability, covered by the soil suitability map of Switzerland, are eventually taken into account. In considering the specified factors assigned to the areas contributing substantially to floods, the requirement of a more optimal characterisation of the flow form process within catchments is met.

The subprocess flow concentration is mainly determined by slope conditions and the length of the river network. To parameterise the flood concentration, the topographical factor (T) can be derived from the proportional correlation of flow velocity (V) and slope of the river network (G), $V \sim G^2$, according to Potter (1953). It is defined from:

$$T = \frac{L}{\sqrt{G}}$$

specified

T = topographical factor
L = length of channel grid (scale 1:25 000)
G = mean channel slope [°]

APPLICATION

By deriving the catchment characteristics described above, the estimation of extreme floods is aimed at. This procedure is achieved in two steps.

The first step covers the estimation of HQ_2 and includes the calibration of a regional transfer function. For this purpose, the specified process orientated basin parameters of 88 Swiss catchments embracing long gauging series and areas ranging from 10 to 200 km^2 are yielded. Consequently, the estimated HQ_2 represents the index value for a temporal extrapolation of the floods.

In the second step, the quotients HQ_T/HQ_2 (for T=1 to T=200 => growth curve) are calculated, all the catchments. It is only by this standardisation that single basins are comparable. By multivariate methods of classification the growth curves are to be arranged in order to find the basin parameters responsible for interpreting the individual growth curve classes. By this means areas without flow measurement can subsequently be allocated to a growth curve class thus permitting their flood flows at a fixed return period to be estimated.

This method facilitates the spatial extrapolation of flood peaks at low frequency and consequently, based on threshold values, an assessment of flood risks within an area, without claim to numerical exactitude. This spatial rating will be carried through for the whole of Switzerland, focusing on a cartographic representation in a form relevant to practice.

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20. Methods for detection and explanation of trends and temporal variability of nitrogen-concentrations in small forested catchments

L. Andersson, K. Sundblad, & A. Lepistö

ABSTRACT

Methods, used in a Swedish-Finnish research project, for studies of trends and temporal variations of nitrogen concentrations and transport from small forested catchments, are described and discussed. Six Finnish and ten Swedish catchments were included in the study, using time series from 1971-1988. The methods used included trend analyses, analyses of relations between hydrology and nitrogen, and GIS-aided multivariate regressions. Dependence between the chosen methods and data sets and the results obtained are illustrated, and the necessity to include natural variations as explanatory factors in trend and regression analyses is stressed. The importance of including information about where in the landscape a change of land-use or land-management has taken place is also illustrated, and GIS is suggested as a tool for including such information in a regression analysis.

INTRODUCTION

The Finnish-Swedish Gulf of Bothnia project, attempts to increase the knowledge of the Gulf of Bothnia environmental status. One sub-project deals with nitrogen transports from forests. The aims of this study are:

* To analyse if there are trends towards increased concentrations and transport of nitrogen from forested catchments

* To explain how trends, temporal and spatial variations are linked to factors such as hydrological and climatological conditions, atmospheric deposition and forestry activities

* To investigate why concentrations and loads vary between catchments

Some results of the project have been published (Andersson & Sundblad, 1991, Lepistö *et al.*, 1991) and the final conclusions will be published during 1993. This paper concerns the temporal aspects of the study. It deals mainly with methodological issues and less with results. Questions are raised concerning the choice of methods and data to include versus the obtained results and conclusions.

DATA BASE SELECTION

Nitrogen concentrations have been measured at the outlet of several small and large forested catchments, draining to the Gulf of Bothnia. The number of catchments that can be used in a study of trends and temporal variations is, however, limited. The time-series must be long enough for detection of trends that reflect not only natural temporal fluctuations. Changes in laboratories or methods for chemical analyses often make part of the time-series unsuitable for trend analyses. Other reasons for excluding catchments can be lack of good discharge measurements. These are necessary for transport estimates. This is especially true for small catchments, where rapid changes of flow rates are common.

Trend analysis is often the first step of an effort to detect and explain environmental changes. In the second step, the availability of databases concerning physiographic, meteorological and land-use factors can limit the number of catchments for analysis of causes for observed variations in the time series of water quality.

There are, however, very few catchments that are optimal for all requirements that one would like. Therefore, compromises must be made, which leave enough catchments to cover the various spatial and temporal characteristics of interest for the problem in focus. Otherwise, when using statistical tools, the degrees of freedom will be too low to make it possible to draw any conclusions from the relationships obtained.

In this study we selected six Finnish and ten Swedish catchments, using time series from 1971-1988 (Figure 1).

The size of the catchments varies from 0.7 to 23 km^2. Some of them do not drain into the Gulf of Bothnia, but they have similar physiographic characteristics as areas within the Gulf of Bothnia drainage basin. For the Finnish and two of the Swedish catchments data were available concerning ammonium, nitrate, and total nitrogen. For eight of the Swedish catchments only nitrate-N concentrations were available. The sampling frequency normally varied between six and twelve samples per year, although an intensive sampling programme (40-60 samples annually) was implemented in one of the Finnish catchments in 1985-1988 (Lepistö *et al.* 1991). The availability of physiographic and land-use data varies considerably. Consequently, all catchments cannot be used in all parts of the study.

TREND ANALYSES

One aim of the project is to assess if there are trends in concentrations and load transports of different fractions of nitrogen in the stream water. For such analyses, is important to choose methods that are not too sensitive to single measurements, autocorrelation between consecutive measurements, or changes in sampling strategy (Grimvall *et al.* 1991).

The inclusion of an explanatory factor in the analysis is a statistical way of explaining observed trends. Such factors can be hydrological and meteorological events, atmospheric deposition, or land use-changes. The correlations can, however, be indirect or coincidental and must therefore be critically examined before any conclusions can be drawn.

Trend tests were made for concentrations of nitrate-N for fifteen catchments, and for total-N and organic-N at six catchments (Lepistö *et al.* 1991). The results of the common linear regression model were compared with a non-parametric trend test (Hirsh & Slack, 1984), which is a multivariate extension of the Mann-Kendal test. This test is based on ranks of monthly mean values of the concentrations, which means that the effect of extreme values will be limited. The test can be used with a covariance term, making it robust to serial dependence.

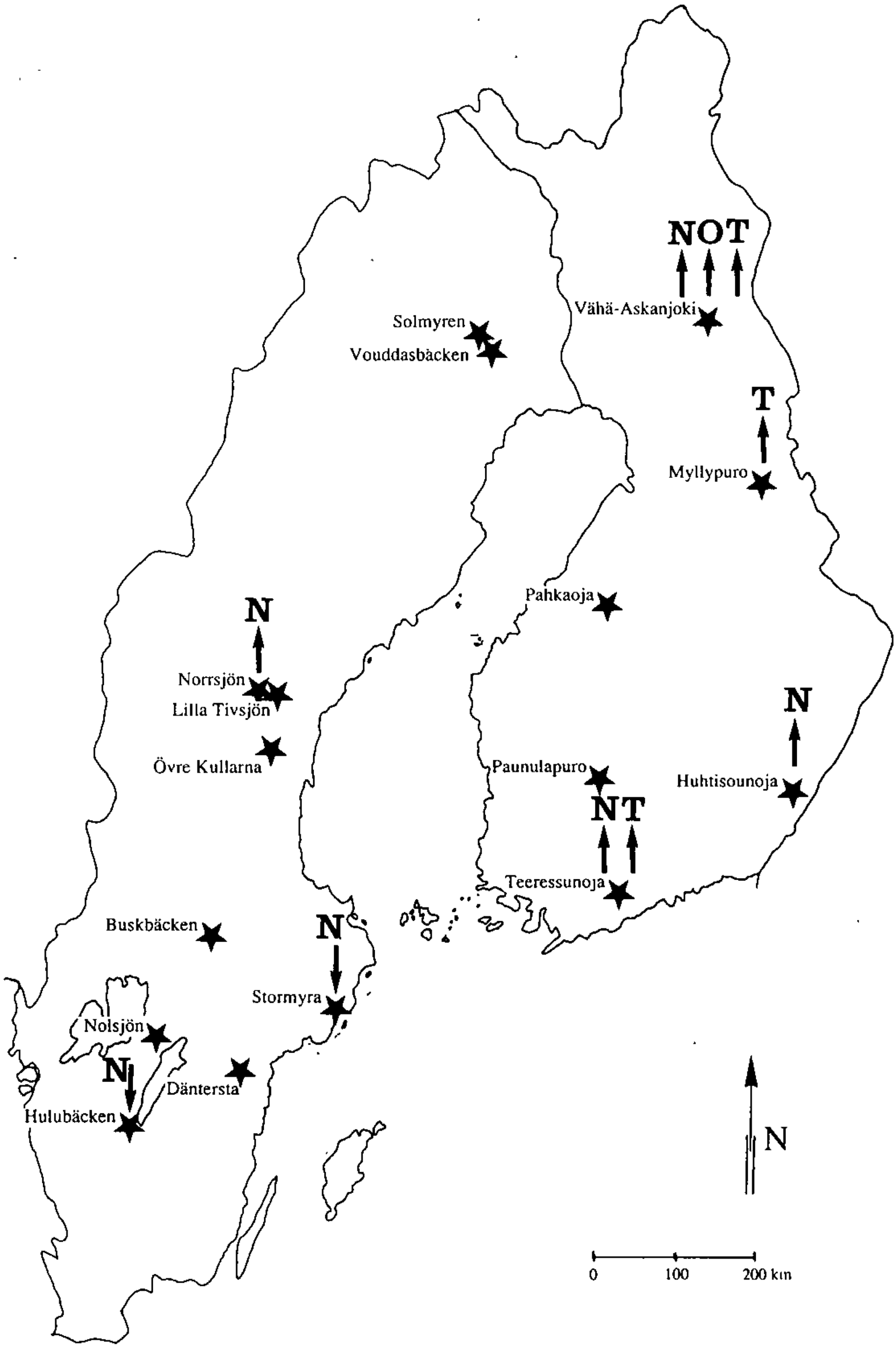

Figure 1 *Catchments used in this study. The arrows indicate increasing or decreasing values over time (Hirsh & Slack test, with consideration of serial dependence) for N = NO_3^--N, O = organic nitrogen and T = total nitrogen*

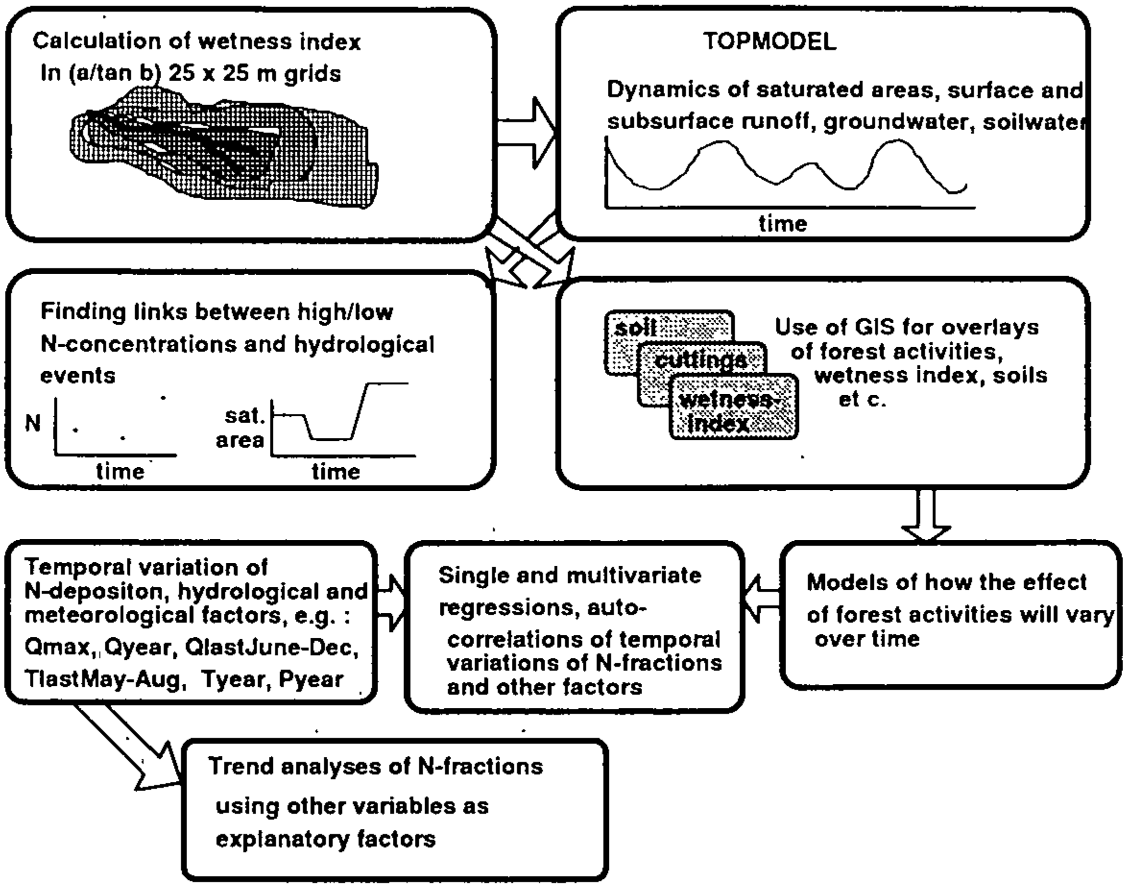

Figure 2 *Relations between the different methods discussed in the text*

The trends on an annual basis are calculated from trends achieved for each month. For some catchments, measurements concentrated on months with high flow (snowmelt and autumn flows). Running the trend tests only for the months with complete time series did not change the level of significance. Removing outliers can, however, be an important part of time series analysis. In some of the series used in this study, most outliers occurred in the first part of the time series, when monthly values often were based on a single sample. In the same series, the sampling intensity was often higher during the more recent years. Therefore, removing outliers often did increase upward trends.

An example of trend test-statistics (T-values) achieved with different tests is given in Table 1. The use of the non-parametric trend test decreased the trend. Simple flow-adjustment (using stream discharge as an explanatory factor) had no significant effects on the observed trends. This is due to weak correlations between stream discharge and organic-N concentrations. This pattern was typical for most of the catchments and for all nitrogen fractions.

When including the covariance-term to consider serial dependence, no significant trend could be detected. The same results were achieved for several of the included catchments. This reflects that the linear regression method is unsuitable for time series of water quality, where serial dependence can be expected. In the final analysis, we have used the Hirsh & Slack test, in order to limit the effect of skewed distributions and serial dependence.

Table 1 *Test statistics (T-values) for trends in organic-N concentrations at Däntersta (1977-1988). Significance levels: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.. **LR**= linear regression, **HS** = Hirsh & Slack, non-parametric test., **Qadj** = stream discharge used as explanatory factor. **Sdep**= Serial dependence considered*

LR	LR, Qadj	HS	HS, Qadj	HS, Sdep	HS,Qadj, Sdep
3.173 **	2.916 **	2.468 *	2.396 *	1.603	1.561

In the time series from Teeressuonoja, significant trends were observed both for atmospheric deposition of nitrogen and for nitrate-N concentrations in the streamwater. The trend in stream nitrate-N concentrations was most significant in April, when spring flow usually occurred. It could not be explained by including April means of discharge, air temperature, precipitation or atmospheric deposition of nitrogen as explanatory factors. Neither could yearly values of atmospheric-N deposition explain the trend.

As earlier mentioned, it is sometimes necessary to use an explanatory factor that considers antecedent conditions. To test the hypothesis that a trend in N-accumulation of nitrogen in the snow could have caused a trend of nitrate-concentrations in the spring-flow, the mean N-concentration in the snow was estimated (Equation 1).

$$\sum_{i=1,j} (P_i/P_{tot})N_i \qquad (1)$$

j = number of months before April when average air-temperature was negative.
P = monthly average precipitation (mm).
N = monthly average N-deposition (mg/m^2)

When using this estimate as an explanatory factor, the April trend for nitrate-N ($P < 0.001$) was reduced to a level that was not statistically significant.

Isotope studies have shown, however, that the snowmelt runoff in Teeressuonoja consists to a considerable degree (70-85%) of pre-event water (Lepistö & Seuna, 1990). This must be considered before drawing any conclusions from the statistical correlation obtained.

At Myllypuro, during the first part of the time series, the sampling programme for total-nitrogen was more frequent than for nitrate and organic nitrogen. In the middle of the study period, nitrogen concentrations were high during a time of forest cutting within the catchment. For the whole study period, the only detected trend was for total nitrogen. This temporal increase in the middle of the investigation decreased the probability of detecting upward trends for the whole period. This effect was largest for nitrate-nitrogen and organic nitrogen, due to the scattered sampling programme during the first years. This is an example of when possible long-term changes due to one factor (e.g. atmospheric deposition) can be hidden by short-term changes due to another factor (e.g. forestry activities).

RELATIONS BETWEEN HYDROLOGY AND NITROGEN CONCENTRATIONS

Flow-adjustment had, with a few exceptions, no effect on the level of significance in the trend test. However, discharge dynamics are probably important for concentration variations.

An example is given from Teeressuonoja, where the sampling programme during the spring-flow was intensive (Table 2). In general, increases of flow caused increased concentrations, but the dilution effect, and decrease of the pool with nitrate available for leaching, did also have to be considered. It is therefore seldom fruitful to use a flow-adjustment based on simple correlations between flow and concentrations for the whole time series.

Other hydrological parameters also have to be considered, i.e. groundwater levels, soil moisture deficits, division between surface and subsurface runoff, and extension of saturated areas. In addition, antecedent hydrological and meteorological conditions will be needed to determine the pool of nitrogen available for leaching.

Such variables are only possible to obtain, with sufficient temporal and spatial resolution, if a distributed hydrological model is used. In our case, we used TOPMODEL (Sivapalan *et al.*, 1987), which is a semi-distributed model based on a hydrological index that is calculated from topography, using accumulated areas and slopes to surrounding cells.

The relations between hydrological events and organic-nitrogen concentrations have been investigated (Andersson & Sundblad, 1991). As an example, the highest concentrations were found when the discharge was low, but the proportion of surface runoff was high. During such events, rain and meltwater will wash away organic-nitrogen from saturated areas. This type of information can be used to build models that combine water and nitrogen transports.

Table 2 *Maximum and minimum values of nitrate-N concentrations in relation to stream dynamics at Teeressuonoja during three spring flows*

	1985	1987	1988
Maximum nitrate-N conc. (ug/l)	820	926	1300
Event	First day in spring with increase in flow	First day in spring with increase in flow	Third flow peak of spring flow
Discharge ($ls^{-1}km^{-2}$)	4.5	4.3	29.4
Minimum nitrate-N conc (ug/l)	290	350	310
Event	Recession after the first peak in the spring flow 3 days earlier	At the only peak of the spring flow	At the last and highest flow peak of the spring flow
Discharge (mm/day)	22.8	16.1	47.7

GIS-AIDED MULTIVARIATE REGRESSIONS

In regression analyses, the parameters are usually the total percentages of geographical factors at different time steps. The environmental effect of changes in land-use or management will, however, often depend not only on the size of the affected area but also where the modifications took place.

In our study, this is considered by using a GIS to make overlays of maps showing forestry activities (drainage, fertilisation and cutting) and maps of landscape factors such as soil type and the hydrological index used in connection with TOPMODEL. This index was used to divide the catchment into three wetness classes with different probabilities of being saturated.

Multivariate regressions were made to explain why concentrations of nitrogen fractions and loads vary over time. To be able to include forestry activities, models for changes of the effect over time had to be suggested. Results from earlier investigations of the temporal effects of forest activities are not consistent. Since we do not know a best model beforehand, a number of models are tested in the regression analyses. Examples of such models are shown in Figure 3. The models are tested with different inputs, achieved from the GIS-overlays, *e.g.* areas in the wettest class, all areas except the driest class, or the total areas.

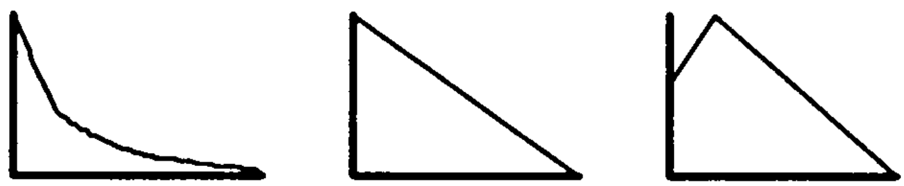

Figure 3 *Examples of models of the changing effect of a forest activity over time*

Inclusion of combinations of factors with the help of GIS is in theory a fruitful development of regression analyses. In reality, the availability of spatial databases is limited. It must also be considered that the construction of such databases is time-consuming, and it is difficult to get the same quality for all of the components. In our study, it is therefore only possible to make these analyses for some of the catchments.

The results of regression analyses are not completed for all basins yet. Those analyses made so far show that it is difficult to find a best model from a multivariate regression due to autocorrelations. The strongest factors in single-factor analyses are often not included in the multivariate models. Some correlations between nitrogen loads and forestry activities have been detected.

CONCLUSIONS

When analysing time series, the result will depend on the chosen methods and data sets. Some detected trends can be due to limitations in the data set, such as seasonality, skewness, and outliers due to, for example, analytical errors or monthly means based on single measurements. It is therefore important to choose a trend test that is robust to these impacts.

Observed trends can also be due to temporal changes in natural hydrological and meteorological conditions. The effects of natural variability must be separated from changes that are due to anthropogenic alterations of environmental conditions. This can be done by including natural variations as explaining factors in the trend test. It is, however, difficult to find the most appropriate parameters to use. Sometimes antecedent conditions have to be considered.

To be able to draw general conclusions concerning long-term environmental changes from statistical analysis of time series, it is necessary to include several series. Otherwise there is a risk that correlations between various factors are coincidental or reflect analytical errors or very specific, local conditions.

When studying the effect of land-use changes on increased nutrient loading, the effect will depend on where in the catchment the change took place. Conflicting results from individual studies could be because this was not considered. If the relevant geographical information is available, a GIS is a powerful tool for finding combinations between landscape factors and land-use changes.

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21. The choice of cell size in digital terrain models: an objective method

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ABSTRACT

A method is proposed based on the theory of information, to measure the quantity of information contained in several DTMs generated with different cell sizes for the same set of digitized contours. The underlying hypotheses is that the quantity of information increases as cell size decreases, while the contours are contributing to the new topographic information appearing in each step, but no significant increment of information will occur below a critical size. The expected result is to determine the optimal cell size that corresponds to the part of the graph where it begins to smooth.

INTRODUCTION

Most hydrologic, geomorphic and ecological research requires a topographic input. Although digitized contour data or triangular irregular networks may be used, a Digital Terrain Model (DTM) based on a regular grid has become widely accepted, because of its simplicity in running algorithms and the possibility of handling the associated database in a Geographic Information System. In many cases such a DTM is produced by interpolation from a set of digitized contours.

Cell size may strongly affect subsequent work. It is self-evident that the resolution of the DTM controls the accuracy of the predictions of any model. A coarse grid may not properly reflect topographic facets in detail, leading to over-simplification of results. On the other hand, a grid which is finer than the underlying topographic information supported by the contours will produce topographic artifacts, such as sinks, dams and terraces which will mislead the performance of the model. This problem is stressed when neighbouring operations are involved, as in the case of downslope flow pathway algorithms, because spurious forms break the continuity of the generated pattern. Another source of problems arises when supplying data for hydrologic comparisons, specially if variables such as radiation or evaporation must be integrated for the whole basin.

The choice of cell size is largely subjective, although objective and automatic methods have been proposed, as for example "progressive sampling" (Makarovic, 1973, 1977). However, that method indirectly evaluates the accuracy of successive DTMs with progressively denser grids.

EXPERIMENTAL DESIGN

DTM resolution can be increased up to a limit that depends on each concrete set of contours. That limit is related to the equidistance of the contours and the relief of the terrain under study. Expressing the problem in terms of the theory of information, the DTM is a message that must reflect the information contained in the initial set of contours. The resolution of the DTM controls the amount of information that it can contain, and if it is excessive, it will include redundant elements. The existence of redundancy influences diversity, and therefore this method is concerned with examining the evolution of the diversity of successive DTMs as the resolution increases.

The steps involved in the proposed method are as follows:

1) delimitation of a representative window within the study area;
2) establishing a sequence of cell sizes for which resolution is doubled on each successive iteration, largely exceeding the limits of reasonable interval considered *a priori;*
3) calculation of DTMs for the different cell sizes;
4) plotting of the values of total diversity according to cell size;
5) calculation of images of local diversity for the DTMs;
6) choice of optimum cell size. In this context, optimum means maximum of total information and minimum of redundancy.

The data set for this work are two windows (Figure 1) containing contours digitized at 5 m intervals from a 1:1000 map of the Izas Experimental Catchment in the central Pyrenees (Alvera *et al.*, 1991). In each window, grids were calculated for different cell sizes (Table 1), employing the inverse distance-squared weighting function (Davis, 1986). The ten nearest points were taken in a search radius equal to the diagonal of the respective window by using a quadrant search, in order to keep a radial constraint. These adjustments were the same for every DTM.

The values for the DTM were rounded to integers, to obtain a precision consistent with the contours. This made it easier to obtain discrete classes with 1 m altitude resolution. In this way, each DTM was considered a collection of objects for which Shannon's Diversity Index (H_T) (O'Neill *et al.*, 1988; Magurran, 1988) can be calculated:

$$H = -\sum_{i=1,S} (P_i) \ln (P_i)$$

where P_i is cell proportion in class i, and S the number of classes.

When calculated as above, total diversity is referred to a whole DTM, and it is not possible to examine the contribution of different zones in the study area. The local diversity (H_L) of each DTM was calculated through the same equation, using a moving kernel of 3 x 3 cells. This produces an image that allows the detection of spatial patterns for this parameter. This procedure was performed with the IDRISI package (Eastman, 1992), that also served to manage the data base for the present work.

DIVERSITY VARIATION WITH CELL SIZE

Generally, H_T values increase as cell size decreases (Table 1). Figure 2 shows that H_T asymptotically approaches a value when cell size decreases. A square root transformation of the cell size was used to get a linear scale.

Table 1 *Calculation of grids for different cell sizes*

Code (*)	Cell size (m^2)	Grid size	H_T	max. H_L	min. H_L
W1-G1	9000.00	24 x 7	3.0847	2.1972	0.9650
W1-G2	1780.22	8 x 14	3.9417	2.1972	0.6365
W1-G3	400.00	16 x 28	4.2261	2.1972	0.5297
W1-G4	100.00	31 x 55	4.3241	2.1972	0.0000
W1-G5	25.00	61 x 109	4.3676	2.1972	0.0000
W1-G6	6.25	121 x 217	4.3681	2.0432	0.0000
W1-G7	3.08	172 x 309	4.3683	1.8310	0.0000
W2-G1	8004.43	8 x 3	3.1203	2.1972	1.2730
W2-G2	2001.11	15 x 5	3.9153	2.1972	0.8487
W2-G3	429.36	30 x 10	4.4813	2.1972	0.5297
W2-G4	107.34	59 x 19	4.5254	2.1972	0.0000
W2-G5	25.89	118 x 38	4.6367	2.1972	0.0000
W2-G6	6.36	236 x 76	4.6561	1.8892	0.0000
W2-G7	1.97	422 x 136	4.6564	1.7351	0.0000

* W1-: Window 1 (20.52 ha, 9827 digitized points ranging from 2100 to 2245 m altitude)
W2-: Window 2 (11.21 ha, 6513 digitized points ranging from 2070 to 2240 m altitude)

The diversity index employed (H_T) represents the information (Margalef, 1957) of each DTM. That information increases as the cell size becomes progressively smaller, and the increment is fast while cell values reflect the complexity existing in the digitized contours. Yet, when cells are too small the problem of redundancy becomes apparent: adjacent grid nodes will employ the same control points with similar weights, and therefore will reach the same interpolated value for a given numerical precision.

Redundancy forces a reduction of the incremental rate of total information. That reduction is related to the value of sum of terms, each one of them having the form $P_i \ln (P_i)$ in the index here employed. As a result, when the series becomes redundant, successive reductions of cell size do not provide anything new, and the increase of total information tends to slow down. This is the reason why H_T shows an asymptotic shape in Figure 2.

What is the value for the asymptote, that is to say, the maximum of information (H_{TM}) possible that a DTM can contain? Initially, theoretical maximum depends on the total number of classes (S):

$$H_M = \ln(S)$$

In this case the value S for each window is equal to the altitude range plus 1. Employing the features derived from the contours, H_{TM} is equal to 4.98 for Window 1, and 5.14 for Window 2. But both values are clearly above the actual asymptotes, which are around 4.4 and 4.7 respectively. Maximum theoretical values are reached when $p_1=p_2=p_3=\ldots=p_i=1/S$, and discrepancy must be related with initial redundance linked to the spatial autocorrelation existing in any topographic surface.

The examination of local diversity supports all the previous considerations. The value of H_L is calculated for each grid cell using altitude values in the surrounding 3 x 3 window. Therefore, H_L varies between $\ln(9)=2.1972$ when all values are different, and 0 when they

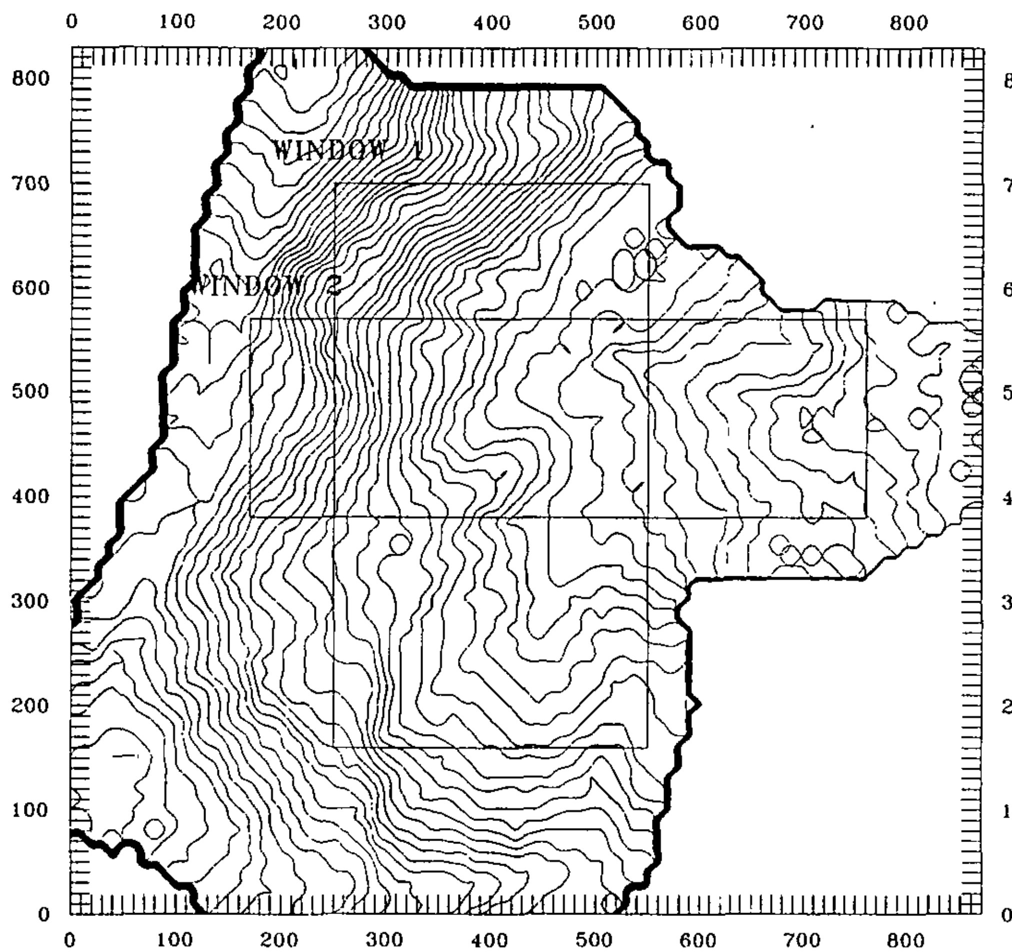

Figure 1 *Two windows of contour data taken from the Izas experimental catchment*

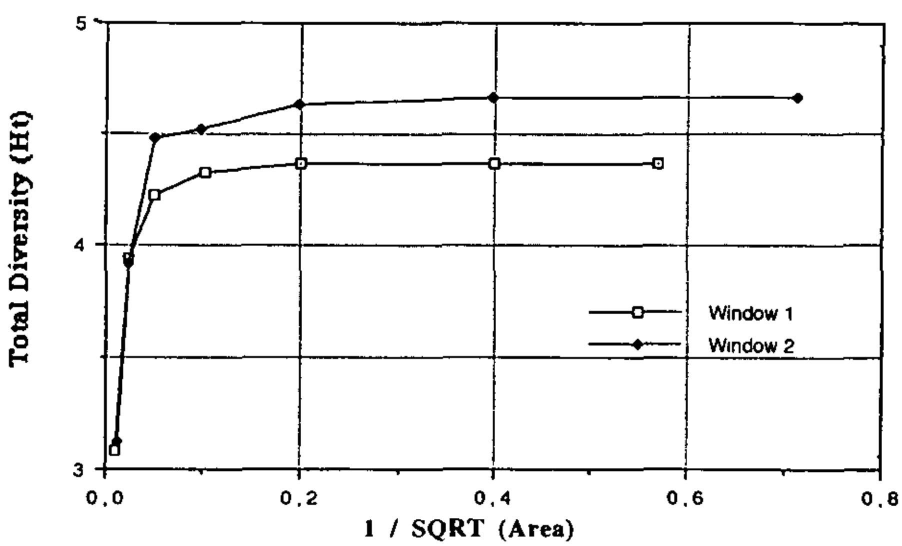

Figure 2 *Shannon's Diversity Index (H_T) for different cell sizes*

are all equal. In a non flat surface, the last case is related with an excessive resolution causing local concentrations of cells with the same value.

Figure 3 shows three images of local diversity built in that way for successive DTM corresponding to Window 1. The first one (W1-G2) presents an unpredictable distribution of H_L, and the maximum possible value is reached there, but not the minimum (Table 1). That is due to the fact that DTM cells tend to have values which are different to each other, and this suggests that the resolution is too coarse for a correct representation of underlying topographic facets. The second one (W1-G4) also presents certain heterogeneity, although the maximum and minimum theoretical values of H_L appear simultaneously. The maximum implies that the resolution can accurately represent topographic variability, whereas the scattered minimum may be related with some flat zones on the area. However, in the third case (W1-G6) the values of H_L are ordered in a spatial pattern that follows contour lines, allowing the detection of redundancy in the DTM. In the same sense, the lack of pixels with the maximum theoretical value leads us to conclude that resolution is excessive for this set of data.

For both windows, the two plots of total diversity (Figure 2) place step 4 (W1-G4 and W2-G4 respectively) at the end of the fast increment zone according to resolution, immediately before H_T starts becoming stable. Of all the performed steps, that is the resolution that best reflects the information contained in the contours, excluding an excess of redundance, and therefore the best choice. Figure 4 shows a tridimensional perspective of three DTM with different resolution levels for Window 1, including the final choice. It can be appreciated how an excess of resolution produces an artificial terrace-like effect in the slopes.

As expected, there is certain convergence in the behaviour of both diversities, total and local. However, this result is not so obvious, and in the case of the Izas Experimental Catchment, it is related with the relative spatial constancy of terrain grain. Otherwise, the examination of local diversity may be useful to identify heterogeneity in such grain, and subsequent need to find a compromise solution or else processing separately the different zones.

CONCLUSIONS

The method here presented offers results which are not ambiguous, and it seems suitable for a more general use. It is based in the theory of information, which allows the direct evaluation of the variables involved in the resolution of a Digital Terrain Model, or any other image. In addition, it is a relatively fast process: the calculations for the largest of the windows, with about 10000 control points, amounted to approximately 30 hours of C.P.U. on a 386 based PC with math coprocessor, most of them without human intervention.

The future development of this method requires two comments. In the first place, the definition of an asymptotic function that relates diversity increment with cell size for a given terrain. A mere statistic adjustment seems insufficient, since it would not provide any theoretical conclusion and, also, data do not have dispersion. In the second place, a calculation of the diversity could be performed on some images directly derived from the DTM, such as aspect and slope, or even on some linear combinations of them all, for example the first factor scores of a principal component analysis. This would allow the consideration of facets of a DTM that altitude cannot solve by itself, as in the case of an ideal cone.

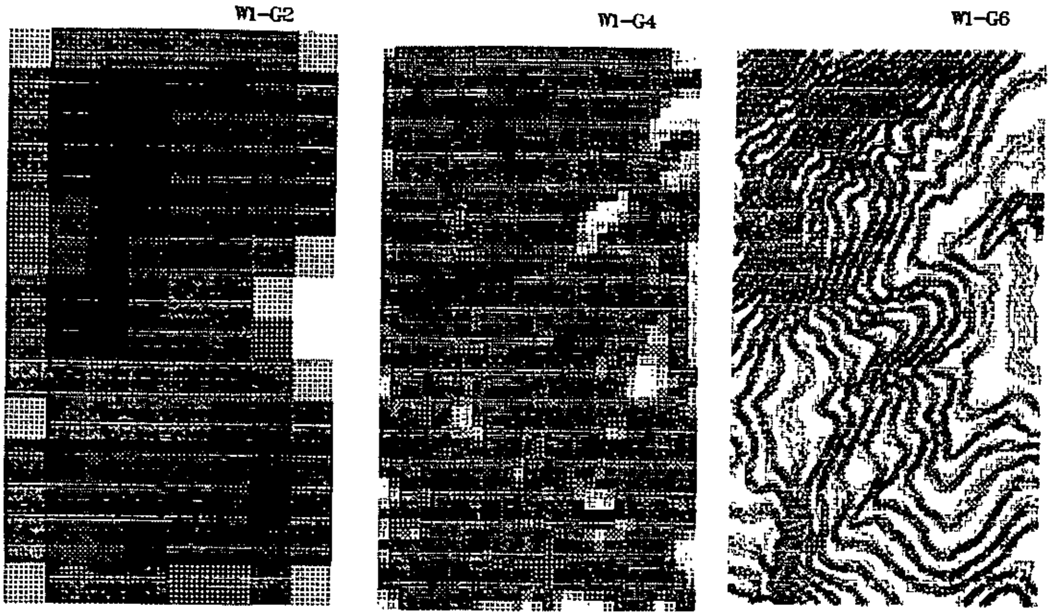

Figure 3 *Three images of local diversity for Window 1*

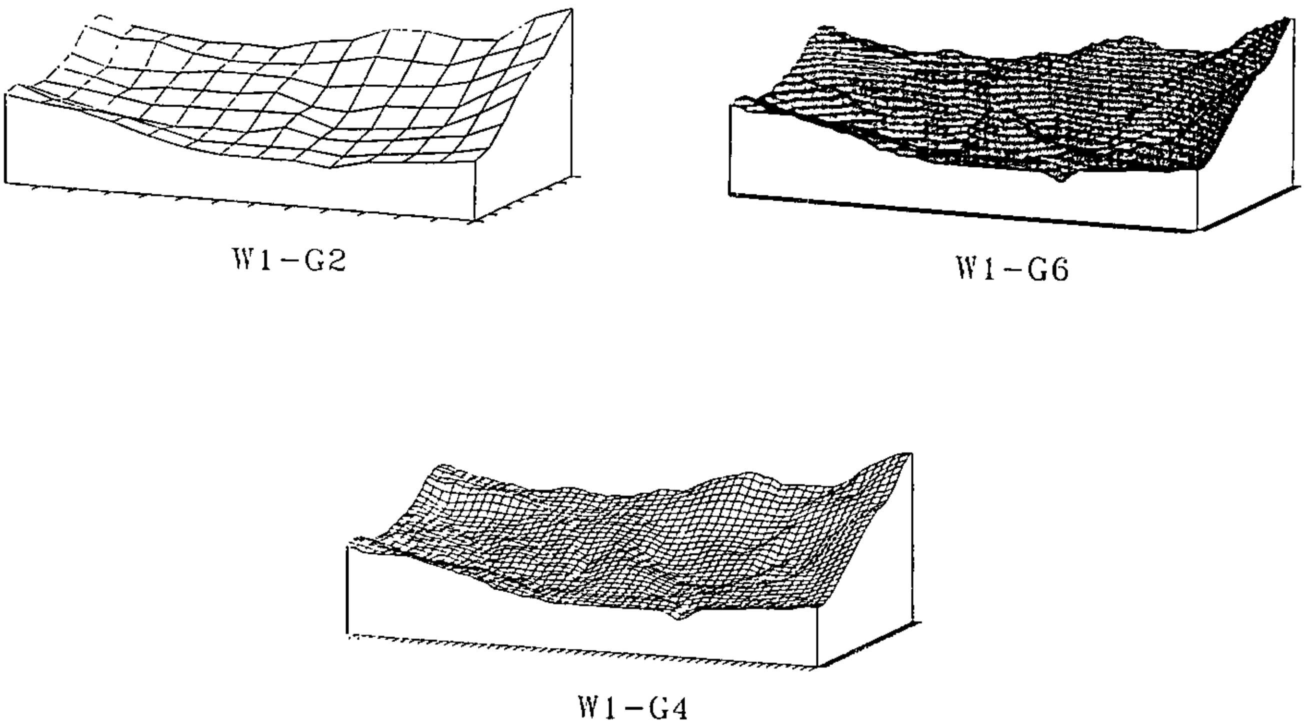

Figure 4 *Perspective views of three DTM with different resolution levels*

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