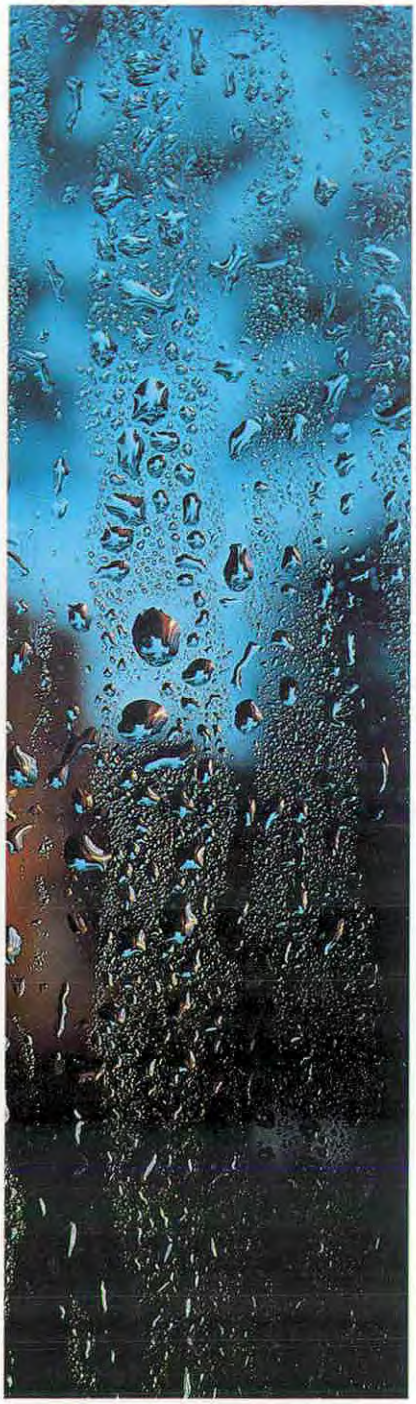
1992 — 1993

REPORT



Institute of Hydrology

Natural Environment Research Council

Foreword

The Institute of Hydrology is the UK's leading centre for hydrological research and one of the most prestigious hydrological research organisations in the world. The Institute has celebrated its 25th anniversary with an excellent year. This annual report contains full details of its scientific programmes and highlights of its achievements.

I succeeded Professor Bernard Tinker as NERC Director of Terrestrial and Freshwater Sciences towards the end of the year under report. I should like to acknowledge the skill and wisdom that he has shown in steering TFSD through some difficult times. I have inherited a strong science and management base on which to build. I have spent much of my first few months at NERC in seeing at first hand the research within the Directorate. This has been immensely enjoyable and I am greatly impressed by the quality and variety of the research whether undertaken on the Science Budget or for the wide range of customer organisations.

A strong feature of the Directorate's research is the degree of multidisciplinarity, interdisciplinarity and collaboration. This collaboration is strong not only within the Directorate's own establishments (the Institute of Freshwater Ecology, the Institute of Hydrology, the Institute of Terrestrial Ecology, the Institute of Virology and Environmental Microbiology, the Centre for Population Biology (Imperial College), the Unit of Behavioural Ecology (Oxford University), the Unit of Comparative Plant Ecology (Sheffield University)) but also with other Institutes and Universities. This collaboration is strongly encouraged through Community Programmes such as TIGER (Terrestrial Initiative in Global Environmental Research) and LOIS (Land Ocean Interaction Study)

Professor C Arme

Director of Terrestrial and Freshwater Sciences
Natural Environment Research Council

Front cover illustration.
1992, the year rain returned to the English lowlands
Photograph Vision One

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Report of the Institute of Hydrology 1992/1993

Natural Environment Research Council

Contents

Appendices

The IH senior management team: (from left to right) Jim Wallace, Tony Debney, Brian Wilkinson, Frank Law, Paul Whitehead and David Gray

Divisional Structure

Professor W B Wilkinson
Director IH

Hydrological Processes – Dr J S Wallace

Large-scale processes; Land/atmosphere interactions; Vegetation & sub-surface processes; Groundwater recharge; Agroforestry; Remote sensing

Applications Research – A G P Debney (Assistant Director)

Water resources; Hydrological impacts; Software; Instrumentation

Environmental Hydrology – Dr P G Whitehead

Water quality modelling; Crop water use; Soil physics; Hydrological forecasting; Experimental catchments; Chemical hydrology; Analytical chemistry

Engineering Hydrology – F M Law

Climate change impacts; Flood distributed modelling; National Water Archive; Flow regimes & environmental management; Flood & storm hazard; Infrastructure hydrology; Hydrologic GIS; LOIS (Rivers) data centre

Administration - A D R Gray

Personnel; Finance; Site services

Director's Introduction

Professor Brian Wilkinson

The Institute of Hydrology was established on 1 April 1968. Together with present and former Institute staff I was delighted to hold an event at the end of this reporting year to celebrate the organisation's 25th Anniversary. The Institute's predecessor, the Hydrological Research Unit, had some 50 staff. Over the years the Institute's national and international reputation has grown steadily, and we now have around 200 staff and are recognised as one of the most prestigious hydrological research bodies in the world.

The past year 1992/93 has been an excellent culmination to the quarter century. Our scientific programme is vibrant, as shown by the full listing of the year's research projects (Appendix 4), and by the output of published papers, commissioned reports, software and instrumentation (Appendix 3). These achievements are only possible through the skill and unstinting dedication of all my colleagues.

Rather than describing the detailed progress in all areas of our science, for this Annual Report I have selected eleven themes, each with an important environmental issue to which hydrological research can make a major contribution and where we have made good scientific progress. This approach provides an opportunity to describe the wide range of multi-disciplinary skills which need to be brought to bear to advance knowledge in an environmental area. The themes draw together research that we are undertaking on behalf of government departments, the National Rivers Authority, private industry and other clients, alongside work funded from the Science Budget.

It is always gratifying when the Institute's contribution to science is publicly recognised and this year I am pleased to report two notable achievements. Firstly I learned that Dr Pam Naden was awarded the Tison Prize at the International Association of Hydrological Sciences (IAHS) General Assembly to be held in Yokohama during July 1993. The prize is given for an outstanding paper published in an IAHS publication by a person under 41. Dr Naden's paper was concerned with *Spatial variability in flood estimation for large catchments.*

Secondly, the River Flow Forecasting System (RFFS) developed under the leadership of Mr Bob Moore by the Institute of Hydrology in partnership with Logica Industry Ltd for the National Rivers Authority, was awarded a British Computer Society Medal as an outstanding project. RFFS is the first centralised, catchment-independent real-time flow forecasting system to be applied to basin-wide flood warning and water management in the UK. It is now used operationally on the Yorkshire rivers.

Our strong science programme would not be possible without the support of a firm funding base. In this respect the Institute has had another excellent year. It may be seen from Appendix 1 that our income has risen in real terms by 10%. This continues the growth in income which commenced in 1989/90 and represents an increase in real terms of 50% over the past four years.

For several years now there have been accommodation problems on our Wallingford Site. This has been exacerbated by the growth in our staff numbers to match the demand for our research over the past four years. The problem has been met through the provision of temporary accommodation on site. This can only be a short-term solution and during the year, with the encouragement of our Council, a proposal to extend our building has been developed.

A new extension would give us the opportunity to regroup some of our staff and develop a much higher profile with the creation of a **National Water Information Centre** and a **National Hydrosciences Library**. The Hydrogeological Group of the British Geological Survey share the site with us and this would be a joint venture. Outline proposals for this new accommodation are given in Appendix 10.

In 1981 the Institute of Hydrology established the Kirkton and Monachyle experimental catchments in Scotland. These are run from a small office and laboratory at Balquhidder. In recent years the Institute has become involved in a much wider range of hydrological research in Scotland and in September of this year we opened an Institute of Hydrology (Scotland) office on the Innovation Park at Stirling University. This will give the Institute's staff in Scotland a more central and accessible location.

Almost every aspect of the Institute's research work involves computing. Our facilities have been greatly enhanced this year by the installation of a distributed UNIX-based system. Storage has been increased by a factor of ten and processing power some one-hundred-fold. The new networking arrangements make these facilities available to our scientists throughout the site.

Together with the large range of high capacity PCs, work stations and portable machines, this puts us in an excellent position to advance most of our hydrological analysis, databases and models. However as part of a number of new research programmes, such as the **G**EWEX* **C**ontinental **I**nternational **P**roject (GCIP) and the **L**and **O**cean **I**nteraction **S**tudy (LOIS), the Institute is developing distributed models at a large catchment or basin scale and linking these to atmospheric or marine models. These will require computing power an order or more greater in magnitude than we currently have at Wallingford. We are exploring a means of providing a supercomputing facility in order to respond to this exciting scientific challenge.

Finally, I must make reference to the Government's White Paper *Realising our Potential - a Strategy for Science, Engineering and Technology* which was presented to Parliament in May 1993. I fully support the policy that scientific and technological research must contribute more effectively to national prosperity and to improvements in the quality of life. I have demonstrated through this and previous annual reports that we are already well advanced in this respect in that the Institute of Hydrology:

- has a well-founded programme of hydrological research that is addressing both UK and global issues;
- has developed — and continues to develop — scientific techniques that are essential not only to the hydrological sciences but have wider application, i.e. they are generic in nature;
- has built many effective bridges between our science and the end user: technology transfer is a fundamental element in our mission;
- has made significant advances with its scientific achievements over the past year which are contributing to wealth creation.

There is, however, no place for complacency and I will ensure that the Institute makes a substantial contribution to the Government's Technology Foresight Initiative.

Brian Wilkinson
Director

IH staff celebrated the Institute's 25th anniversary on 1st April 1993.

* **G**lobal **E**nergy & **W**ater **Ex**periment (GEWEX)

The global perspective

Every Division in the Institute of Hydrology is involved in researching hydrological aspects of global environmental change. This strong emphasis is explained by the pervasive role of the hydrological cycle in the processes of global environmental change: climate change and the greenhouse effect, desertification and dryland degradation, pollution of water bodies and catchments, and deforestation.

Intense research interest at IH is matched by involvement in external programmes. On the national level, collaboration with the UK Meteorological Office's Hadley Centre for Climate Predication and Research is aimed at model improvement, and the office of the TIGER (Terrestrial Initiative in Environmental Research) community programme is located at the Wallingford site. Internationally, IH hosted meetings of the World Climate Programme – Water and the NATO Special Programme for the Science of Global Envir-onmental Change. Individual scientists too are active in international programmes, e.g. IDNDR, WCP, GEWEX, GCIP, EFEDA, BOREAS and IGBP (see Appendix 11).

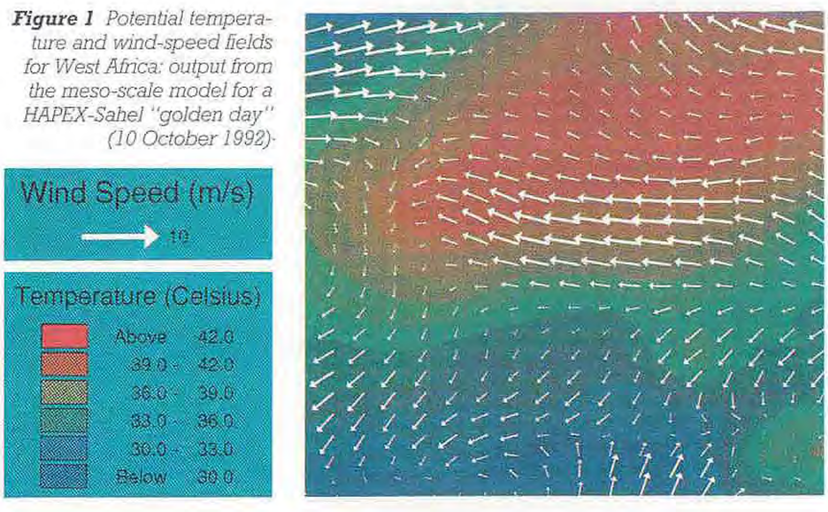
Research into the global environment is focused at the land surface, where the vertical and horizontal redistribution of water and energy takes place, where water is important in the carbon and other cycles, and where climate change impacts on water resources will be felt.

The sixth planning meeting of the World Climate Programme – Water was held at IH from 1-5 March 1993

Land surface processes

The Institute is developing new models of land surface processes. These descriptions, termed Soil Vegetation Atmosphere Transfer (SVAT) schemes, allow simultaneous calculation of energy exchange between the land surface and the atmosphere, and phase change through evaporation and transpiration. An important characteristic of SVATs is their ability to cope with heterogeneity and scale changes. Ideally they are calibrated against observations from field campaigns and remote sensing. Computer code has to be optimised for efficient running within the framework of General Circulation Models (GCMs), where SVATs provide the lower boundary.

Figure 1 *Potential temperature and wind-speed fields for West Africa: output from the meso-scale model for a HAPEX-Sahel "golden day" (10 October 1992).*



A notable achievement has been the development of the MITRE model. This collaboration between IH and the Hadley Centre incorporates the most up-to-date data sets and understanding of processes. MITRE is being implemented in the Meteorological Office's new "Unified Model", designed for both weather forecasting and climate prediction.

Another SVAT development has been the sparse canopy model, calibrated using data from the HAPEX-Sahel campaign in Niger, West Africa. Such terrain is representative of large areas in low latitudes where bare soil and vegetation coexist on a scale of tens of metres, providing an intriguing and difficult surface to model: the bare soil dominates the heat exchange and the vegetation controls evaporation. On a larger scale, the representation of the complex mosaic of land cover types within a single GCM grid cell, typically hundreds of kilometres across, is a difficult challenge for hydrologists. The fine-mesh data collected during HAPEX-Sahel has allowed a meso-scale version of the Unified Model to be developed for West Africa under a joint project with Reading University and the Meteorological Office. Figure 1 is an example of the model output, which is providing important insight into interactions between patches of different vegetation and soil water. An example is the "forest breeze" caused by differences in the heat balance which develops around areas of vegetation.

Such interactions typify phenomena on a smaller scale than the GCM grid, but whose effects need to be aggregated into large-scale SVATs. Aggregation strategies range from using a single set of parameters to represent grid cell to complex sub-models describing vegetation cover independently but allowing for interaction. The meso-scale model will help to explore this range to arrive at the simplest adequate description of the system.

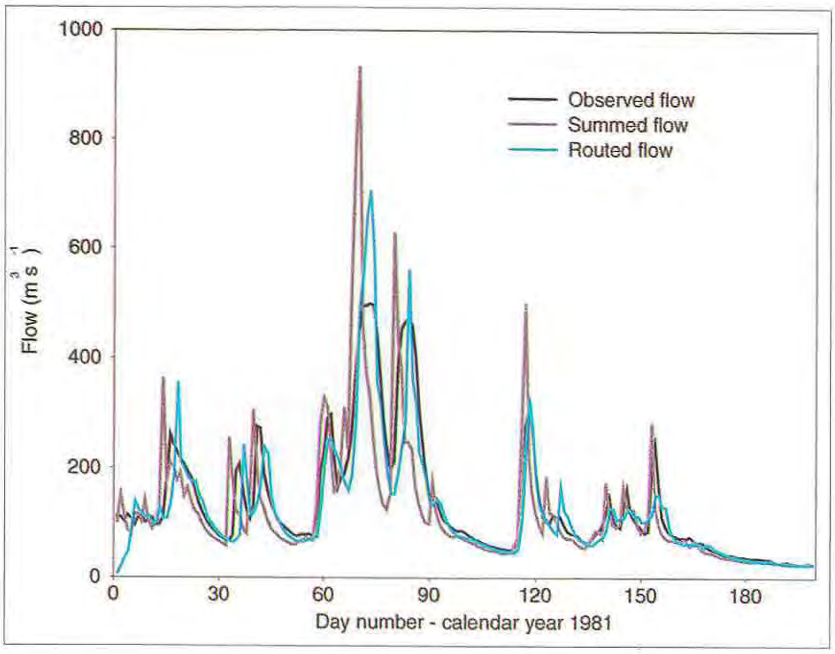


Figure 2 *The significance of river routing. Observed small catchment flows are used to obtain generated runoff for 40 by 40 km squares within the Severn basin.*

Macromodel

Current GCMs inadequately describe the horizontal movements of water from a grid cell to its neighbours at ground level. Macromodel research anticipates a future generation of GCMs in which river and aquifer flows are modelled explicitly. This TIGER programme activity involves IH and university groups at Newcastle, Imperial College and University College London.

The development of a macromodel requires a fundamentally new approach. Most traditional hydrological models are designed simply to replicate observed runoff at a catchment scale (usually less than 1000 km^2), and rely heavily on calibration to achieve this end. However, the context in which macromodels are being developed requires that the model be capable of automatic operation at any point on the earth's surface, using globally available data from cartographic sources or remote sensing, with minimal tuning of model parameters. Furthermore, not only runoff is required of Macromodel but also vertical fluxes and effective linkages with ecological processes.

The key issue is one of scale. GCMs currently operate on a grid scale of more than 100 km, whereas hydrological and ecological variability is found at scales of less than 1 km. Thus, methods have to be developed which will operate at the larger scale but which will also accommodate important sub-grid variability. At this smaller scale, work has focused on the characterisation of hillslopes using topography, land use, and soil type. The hillslopes are regarded as fundamental units for runoff generation, and parameter sets are currently being sought. At the larger scale, a method for river routing has been developed and is illustrated here using observed small catchment flows to obtain the generated runoff. The routing model uses the network width function which describes the spatial positions of mapped river channels as a plot of the number of river channels against distance from the basin outlet. The function is used in conjunction with a linear routing scheme. Figure 2 shows the significance of river routing in daily flow simulation in the Severn basin (around 10,000 km^2). Simply summing the generated runoff produces peaks which are too large and too early; routing reduces the peaks and rectifies the timing.

The routing scheme adopted has two major advantages. First, because the scheme is linear, the basin can be subdivided on the basis of geology, rainfall, grid squares or other appropriate units and the runoff generated within each unit routed independently to the basin outlet. In future, the hillslope analysis will be used to define hydrologically homogeneous areas within a basin and the hillslope model used to generate the associated runoff. The second advantage is that, for the catchments so far considered, the routing has been shown to be independent of map scale, i.e. unaffected by whether the network width function is derived from 1:50,000 map sheets or from the much coarser 1:250,000 maps. This finding is important in applying the models to areas of the globe which are poor in data.

These macromodel developments were envisaged initially in the context of climate modelling, but have also been motivated by other concerns: management of continental-scale river basins, impacts of climate change on water resources, ecological impacts and changing biogeochemical balances.

Field experiments

SVATs and Macromodel are only as good as the field observations that lead to their mathematical

Figure 3 *Micrometeorological instrumentation in a clearing site in Rondonia, Brazil*

form and provide their calibration. Great emphasis has been placed by modellers on the more explicit representation of spatial heterogeneity. This trend has influenced the types of field experiment that have been run.

The ABRACOS (Anglo Brazilian Amazonian Climate Observation Study) project has collected data on evaporation, heat flux and soil moisture from a forest clearing near Manaus in central Amazonia. The data have been used to calibrate the land surface sub-model of the UK Meteorological Office GCM at the Hadley Centre. The climate effects of deforestation are to be estimated from simulation experiments run with land surface parameterisations, calibrated against field data for the existing forest in the control run and for the pasture which replaces it in the deforested run.

Simultaneous measurements of evaporation from rainforest and grass have been made for the first time at a pair of sites closer to the edge of the Amazon Basin. These sites suffer longer and more severe dry seasons. Comparison of the response of the different vegetation types to increasing soil moisture deficit shows that the greater rooting depth of the forest acts to maintain high levels of transpiration through the dry season; whereas grassland transpiration is reduced. It is effects such as these which feed back to produce systematic changes to weather patterns and thus the climate.

An extensive international programme involving about 30 teams from Europe and the USA carried out data collection and analyses for contrasting vegetation types in central Spain under the auspices of the European Field Experiment for Desertification-threatened Areas (EFEDA). The Institute obtained a continuous run of energy and water balance measurements for a dryland area, including a sparse arable crop and vines, over most of their development period. The results have already produced useful information on the behaviour and water use of crops under arid conditions. They are also now being used, together with data from other organisations, in the SVAT scheme described earlier.

It has long been known that plant growth responds positively to increased amounts of carbon dioxide in the atmosphere. There is little direct information, however, on response at the ecosystem level. CLIMEX is probably the world's largest experiment in a glasshouse using double-CO_2; it is being led by IH and funded by the EC. Two giant greenhouses in southern Norway are equipped to evaluate the effect of CO_2 enrichment over an entire headwater catchment. The atmospheric CO_2 within the greenhouse is enriched from the 355 ppm usually present to 560 ppm (double the pre-industrial level) and the air temperature is raised by 5 degrees Celsius above ambient. The IH interest is in the effects on drainage water quality and biogeochemical cycling; other partners in the consortium will be studying biological responses.

Impacts of climate change

It is prudent to assess now the possible impacts of climate change on water resources, even though predictions of future climate are very uncertain. Past studies at IH and elsewhere have investigated the impacts on water quantity and quality, many based on the Department of the Environment's climate change scenarios. Their results provided

Figure 4 *Measurement of energy and water balance for dryland vineyard in La Mancha, Spain, during EFEDA*

the basis for a joint IH/Institute of Freshwater Ecology report to the National Rivers Authority (NRA) concerning the implications of climate change to their operations and their research requirements. The approach was to consider the sensitivity of such NRA functions as water resources, flood defence, fisheries and navigation to a range of hydroclimatic changes including rainfall, runoff, groundwater and water chemistry. The report, which has been widely circulated within the NRA, advocates the development of policy statements for these areas of activity.

The main objective of one project, funded by the DOE's Water Directorate, was to explore the degree to which different regions of the country display different sensitivity to changed climates. The approach was to run a hydrological simulation model with perturbed input climates. The study focused on monthly river runoff and found that the south and east of Britain — the driest part — was generally the most sensitive to changes in rainfall and potential evaporation.

Two other findings which emerged from the DOE study have potential significance for water resource planning. Firstly, the effects of a given change in climate vary considerably between catchments within a region. Secondly, the shorter the period over which impacts are assessed, the greater is the relative impact of a given climate change scenario. For example, summer season flows frequently exhibit a greater percentage change than annual runoff. Figure 5 shows the percentage change in monthly runoff for two catchments, under a scenario which assumes higher evaporation, higher winter rainfall and no change in summer rainfall. The Greta is an upland catchment, and the big reduction in April flows largely reflects a reduced contribution from snowmelt in a warmer future. The Wensum is a lowland catchment in an area where annual potential evaporation is already close to annual rainfall.

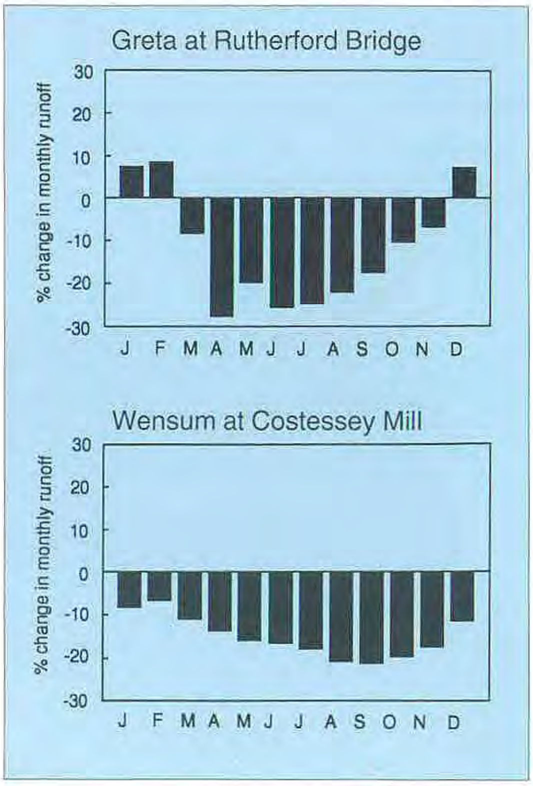
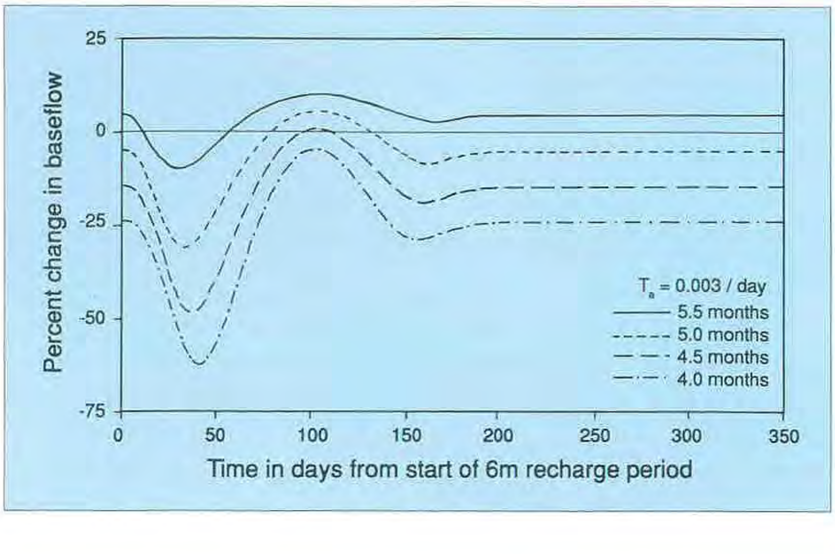


Figure 5 *Percentage change in monthly mean runoff, under a scenario with increased evaporation, wetter winters and no change in summer rainfall*

A parallel study for DOE addressed the sensitivity of river water quality to climate change. Again simulation models were run with scenarios for changes in river flows and water temperature. Changes in water quality were found to vary considerably between scenarios and between catchments, depending on the precise climatic and geological characteristics of the catchment. Higher water temperatures affect the rate of various bio-chemical processes, such as nitrification and denitrification, but a rise in temperature is generally less important than the change in river flows (and hence dilution) associated with changes in rainfall and evaporation

Climate change also has consequences for groundwater resources: a recent desk study looked at the response of idealised aquifer/river systems to climate change. This was represented as a region of aquifer between a groundwater divide and a river: this distance defines the aquifer 'length'. In high-transmissivity, low-storage aquifers, storage and baseflow contributions changed rapidly when recharge changed. Any delay in the onset of recharge in autumn may markedly affect low flows in rivers supported by baseflow from a rapid-response aquifer. Figure 6, based on a river fed from a typical chalk aquifer, shows the reduction persisting, even if the annual volume of recharge increases. For slow-response aquifers an increase in winter recharge volume may increase baseflow to rivers all year round, even where the period of recharge has been reduced. After a change in climate, even a gradual one, such aquifers may show considerable delay before reaching a new storage equilibrium.

Figure 6 *Percentage change in equilibrium baseflow for reduced recharge periods (from the present six months), with maximum recharge set at 15 % above its present value ($T_a = T / SL^2$, where T is transmissivity, S is storage and L is aquifer 'length'*



Watching water from space: microwave remote sensing

Until recently, cloud cover has been a major factor limiting the use of airborne instruments for hydrological observations, but satellites carrying microwave sensors can now monitor changes on the Earth's surface on a regular and predictable basis. This presents a tremendous opportunity for hydrologists at a time when research is extending beyond traditional river catchment studies to address problems of hydrological change occurring on regional and global scales.

Hydrological measurements of variables such as rainfall or evaporation have traditionally been taken at a single point, and spatial averages derived from them using a range of techniques. More recently, portable data loggers have made it possible to sample much more frequently but the relatively high cost of instrumentation has severely limited our ability to sample as widely as we would like. It is to this aspect of wide areal coverage that remote sensing has so much to offer.

The global water cycle is now recognised as being a key component controlling the Earth's energy circulation as a result of atmospheric transport, latent and radiative heating, and through redistribution of water over the surface. Current studies are centred on scaling up our knowledge of hydrological processes based on point measurements to provide physically-based estimates of hydrological variables at scales suitable for input to regional and global models of energy transfer (see *The global perspective*). Microwave remote sensing is playing an important part in the provision of data suitable for this scaling-up using the European Space Agency ERS-1 satellite radar.

The microwave part of the electromagnetic spectrum used for remote sensing covers a much broader range than is available in either the visible or infrared wavebands. This allows considerable flexibility in matching sensor design to observation requirement. For example, at low frequencies (long wavelengths) microwaves can penetrate cloud, rain, dry snow and vegetation to provide information on the underlying soil, whilst at high frequencies, precipitation can be measured as a result of microwave emission and scattering from falling rain. By measuring at more than one frequency or polarisation, further information on surface interactions can be obtained.

Two main types of microwave sensor are available: radiometers, which measure the natural emission of energy from a surface as a function of its temperature and emissivity, and radars, which illuminate their target with a beam of microwave energy and record the backscattered signal. For most hydrological applications, wavelengths of several centimetres are used in both passive and active sensors. For radiometers on satellites, physical limitations on antenna size currently limit available ground resolution to around 100 km, whilst satellite radars can resolve targets on the ground which are only 10–20 m apart. Consequently, radiometers are better suited for data collection at the continental–global scale, whilst radars are more appropriate for measurement at the river catchment–regional scale. A combination of active and passive microwave remote sensing is likely to be required to describe surface variability over the full range of scales.

Surface soil moisture applications

Soil moisture content exerts an important control on the transfer of energy and water at the land surface. For most parts of the land surface, the availability of soil moisture determines the rate of evaporation, as well as controlling the development of vegetation. The surface soil layer is where the largest changes in moisture take place and this strongly influences energy exchange. This is also the region which is detected by remote sensing. Changes in surface soil moisture affect the dielectric properties of the soil which, at microwave frequencies, directly affect its emitting and backscattering properties. The ERS-1 **S**ynthetic **A**perture **R**adar (SAR) is well configured to detect these changes, but field validation to determine the effects, primarily of vegetation, was required.

Under a NERC Special Topic Grant, test sites in the UK and in the Republic of Niger were used to examine the performance of the ERS-1 SAR under predominantly wet and predominantly dry conditions.

The test area in Southern Niger was at the HAPEX-Sahel southern super-site, 25 km south-east of the capital, Niamey, on sand plain soils which are generally used for agriculture. Three main types of vegetation were present: millet crops, fallow savannah (small, widely-spaced shrubs with tall grasses) and open degraded forest known locally as tiger bush. All three were comprehensively instrumented to monitor changes in profile soil moisture during the transitions between dry season (October to May) and wet (June to September). At the time of satellite overpasses, soil moisture in the surface layers was measured, primarily with the newly-developed IH Surface Capacitance Insertion Probe (SCIP), and combined with vegetation moisture and biomass data. Figure 7 shows the mean soil moisture and vegetation conditions on days when five ERS-1 images were acquired during 1992.

ERS-1 overpass at 22.24 GMT	Soil moisture	Vegetation development
14 May	Very dry (<1%)	Fully senesced
23 July	Moist (8-12%): two days since last rain	Early development
27 August	Moist (8-10%): ten hours since last rain	Fully developed
1 October	Dry (~1%)	Dry millet standing or lying as straw
5 November	Very dry (<1%)	Mainly senesced, some millet straw removed

Figure 7 *Soil and vegetation conditions at the HAPEX-Sahel southern super-site, Niger, at the time of acquisition of ERS-1 satellite images*

Figure 8 is a time-series composite of 3 ERS-1 SAR images acquired in May, July and August which enables the main vegetation types to be discerned and shows two transects, the most northerly passing through a 2km x 2km square feature which is the ICRISAT agricultural research farm. This is an area of high radar backscatter which results from mechanically ploughed plots which are not found in the surrounding agricultural area. The transect to the south traverses both tiger bush and agricultural land.

Figure 9 shows the radar backscatter along this southerly transect for each of four satellite passes. It shows that the driest, vegetation-sparse conditions in May produce the lowest backscatter, whilst the wettest (surface) conditions in August produce the highest. The intermediate months of July and October follow a similar pattern of peaks and troughs as May and August and lie in the correct order according to their wetness. On the whole, it appears that seasonal variations in soil moisture in Niger have a much greater influence on radar backscatter than those of vegetation, which will help future monitoring in the climatically sensitive Sahel.

In the UK, ERS-1 data have been acquired every 35 days for a whole annual cycle over two grassland test sites in the Thames Valley area, one on heavy clay soil and the other on sandy flint soil over chalk. Instruments have been installed at both sites to monitor soil moisture conditions within the top metre and the resulting measurements used to test a number of models relating surface soil moisture to moisture throughout the soil profile. An important aspect of this work is to determine the effects of changes in grassland vegetation and soil type on the sensitivity of the radar to variations in soil moisture at the surface. The high spatial and temporal resolution of the satellite radar data aids the separation of vegetation and soil moisture effects but this would be further enhanced with a more frequent repeat period, such as seven days, where changes in vegetation would be minimal.

The UK ground data set is large but incomplete. Before conclusions can be drawn from it, quality control and instrument intercalibration are needed and the effects of dew, vegetation and roughness must be quantified. Figure 12 is an initial plot of volumetric soil moisture at two sites, Cholsey and Chieveley, against radar backscatter. The trend is that soil moisture increases with increasing

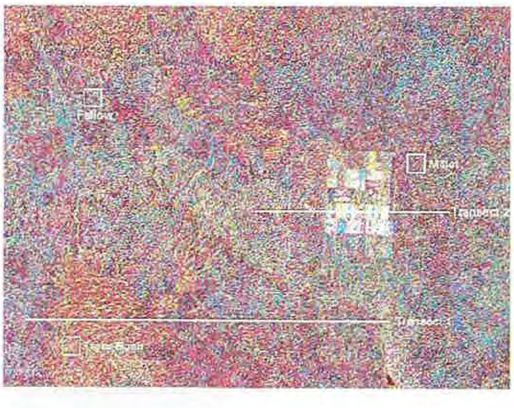


Figure 8 *Multitemporal ERS-1 image of HAPEX-Sahel southern super-site showing main vegetation types and radar backscatter transects. 14 May 1992 = Red, 22 July 1992 = Green, 27 August 1992 = Blue.*

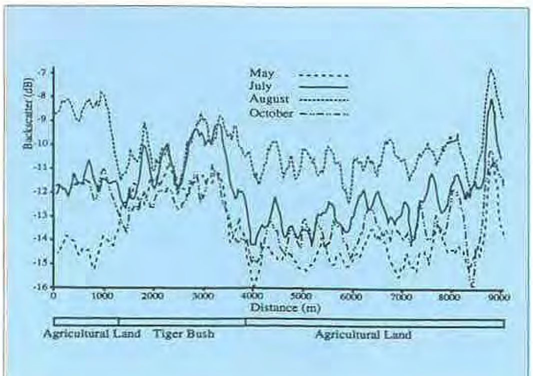


Figure 9 *Variation in ERS-1 backscatter over the HAPEX-Sahel southern super-site. Lowest backscatter occurs in May (dry season) highest in August (wet season).*

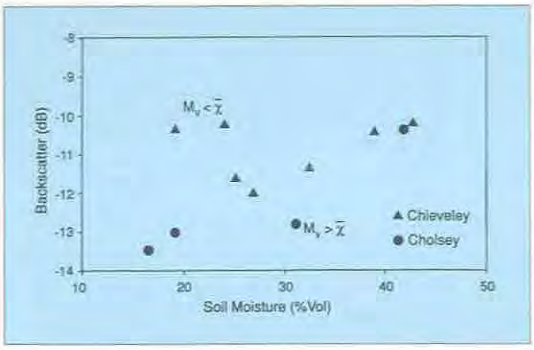


Figure 10 *Relationship between mean radar backscatter and mean 0-5 cm soil moisture for the Cholsey and Chieveley test sites*

backscatter. Outlying points correspond to dates when vegetation moisture and bulk density were above or below the mean, agreeing with other research findings that the presence of vegetation reduce the sensitivity of radar backscatter to soil moisture. Better intercomparisons should come from soil moisture data normalised in terms of field capacity, whilst data from different vegetation and roughness regimes should enable simple backscatter models to separate more specifically the effects of soil moisture.

River flooding

Each year, river and coastal flooding results in major loss of life and property worldwide. Most significant of the major flood events experienced in 1993 were those in Bangladesh, northern India and Nepal which resulted in over 3,000 deaths, whilst those in the Mississippi basin resulted in property losses in excess of $10 billion. Information on basin-wide floodwater extent is required both in the short term for the direction of relief efforts to areas of greatest need, and in the longer term for improving the performance of basin-scale rainfall/runoff models through the provision of floodwater storage data and the location of key points controlling river flow.

In the past, satellite observation of floods have been hampered by clouds and high resolution data have not been available in near real-time. Initial tests in the UK have shown that synthetic aperture radar data from the ERS-1 satellite can overcome most of the imaging problems associated with river flooding, whilst the fast delivery processing system operating from the European Space Agency Kiruna receiving station in Sweden, has demonstrated the feasibility of processing and distributing satellite SAR images in near real-time. What is now needed is satellite repeat coverage every few days to enable flood events to be adequately monitored and this should become feasible in 1995 following the launch of the Canadian Radarsat satellite.

On 4th December 1992, a 1-in-5-year flood event on the River Thames was observed by the ERS-1 SAR. Within this single ERS-1 image, flooding was observed along 400 km of mainstream and tributaries from the headwaters of the Thames to the western outskirts of London. As a means of testing the ability of the SAR to differentiate floodwater from surrounding saturated land, aerial photographs were taken along most of the above mainstream within two hours of the satellite pass. Figure 11 is typical of the extensive flooding which occurred upstream of Oxford. The production of flood extent maps from the aerial photographs was carried out after those derived from the ERS-1 SAR images, so as not to influence the interpretation of the satellite data. Figure 12 compares floodwater extent derived from the ERS-1 radar with that from the aerial photographs.

Figure 11 *Aerial photograph of flooding near Oxford used for validation of ERS-1 satellite radar image*

Figure 13 is an extract of the ERS-1 SAR image acquired on 4 December 1992. In general, the floodwater is quite well defined as a dark area of low radar backscatter, but a number of areas of confusion are apparent. By making use of the temporal imaging capability of ERS-1, an improvement in flood area delineation was possible. Figure 14 is a colour composite of three consecutive ERS-1 passes, each with a time separation of 35 days, which were acquired before, during and after flooding on 30 October and 4 December 1992 and on 8 January 1993 respectively. Overall, the image is rather colourless, except for a few individual fields, because there was little land-use change within these three winter months. The time series image enables floodwater to be separated from permanent water bodies, such as old gravel pits which are common in the Thames Valley, and these generally appear black.

Overall, these first results of flood mapping by satellite radar are extremely encouraging in terms of their accuracy and hydrologic significance as they enable flooding within an entire river system to be observed in a single overview. In terms of disaster mitigation, such information, provided it can be acquired and distributed in a timely fashion, could play a key role in the direction of aid following major coastal or inland flooding. This should now be feasible as the continuity of satellite SAR is assured to the end of the century and beyond through the approved programmes of ERS-2, Radarsat and the EOS polar orbiters.

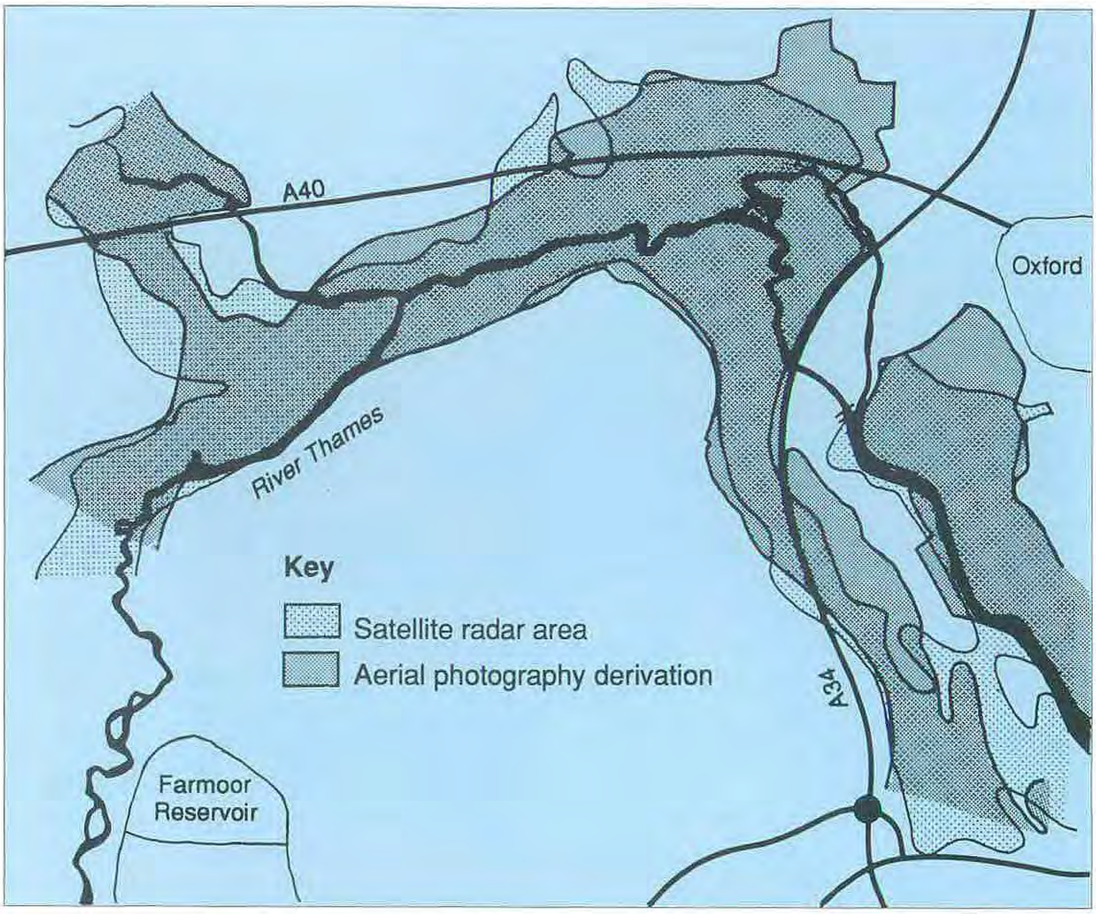


Figure 12 *Floodwater extent on River Thames north of Oxford derived a) from aerial photographs, red line; b) from ERS-1 radar, blue line.*

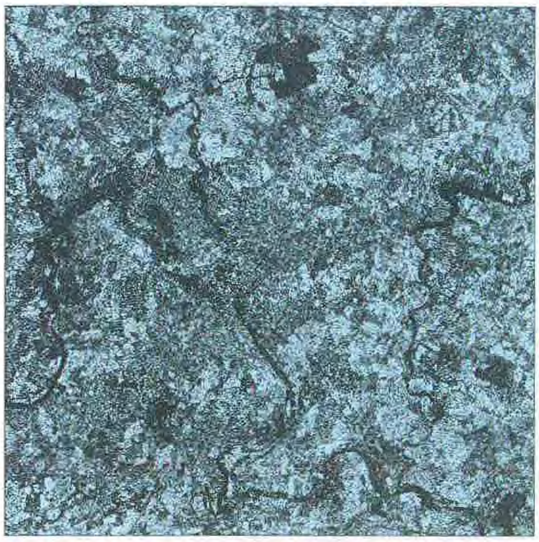


Figure 13 *Single band linearly-stretched ERS-1 image of flooding on River Thames and tributaries around Oxford. Extensive flooded area at top centre is Otmoor wetland.*

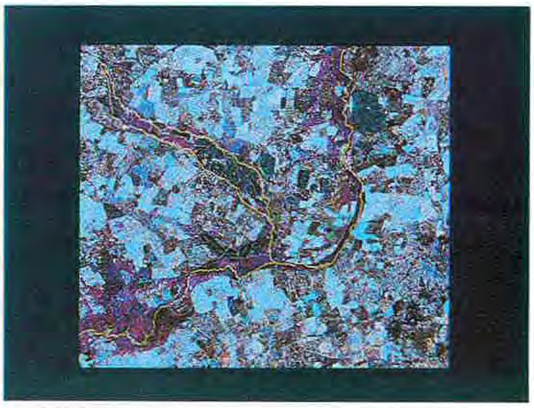


Figure 14 *ERS-1 temporal composite of flooding in the Upper Thames. October 1992 = Red, December 1992 = Green, January 1993 = Blue. Course of River Thames and River Windrush tributaries, yellow; floodwater, purple; permanent water (gravel pits and reservoirs) dark blue.*

Understanding regional hydrological behaviour

Catchments are central to much of the Institute's research. They form natural units of study, and their outputs (water and biochemical fluxes) provide an integration of the processes occurring within their boundaries. Changes demonstrated at the catchment scale are generally more relevant to engineering practice than small-scale plot studies. A proper understanding of the processes operating at a catchment scale may allow that understanding to be transferred to other catchments where only sparse data have been collected.

IH experimental catchments — Plynlimon, Coalburn, Llanbrynmair and Balquhidder

The hydrological studies at Plynlimon and Llanbrynmair in mid-Wales, Coalburn in northern England and Balquhidder in central Scotland are based on small headwater catchments. Although of small size in relation to their downstream river basins, the major controls on the hydrological response of these catchments are fairly typical of those operating over a major part of the upland areas of Britain. The uplands account for 30% of the total land area, but some 70% of the exploitable water resources.

Physical process studies are integral to this catchment approach. Models of their behaviour, developed and tested on data from research sites, can be applied (wholly or partly) to water resource and water quality problems in larger catchments — provided that the model parameters can be adjusted to account for differences in geology, topography, soils, vegetation, land use and land management. External perturbations to these systems — including land-use change, river and reservoir engineering works, inter-catchment transfers and climatic shifts — can be quantified from optimised values of the models' parameters or by comparison with control catchments in the same area. Different future scenarios can be developed by studying changes in the optimised parameters.

Figure 15 *Clear-felling, Plynlimon, mid-Wales*

The basis of the Institute's network of these research studies was principally established using NERC funds, although the role of government bodies, including the Welsh and Scottish Offices, NRA, DOE and the Forestry Commission, has been crucial in sustaining and developing the research momentum. The NERC funding has underpinned the long-term data collection and processing procedures, and sustained the infrastructure of the experiments. This balance of strategic funding and short-term commissioned and targeted research reflects the long-term commitment of the Institute of Hydrology to developing the hydrological sciences, alongside the need to conduct relevant scientific research into matters of current concern.

The catchments also serve to test and develop new instrumentation, and to investigate new hydrological techniques that will have practical applications elsewhere. Academic study by staff from other NERC Institutes is encouraged, as well as by members of the higher education community, to help to train the next generation of hydrologists and environmental scientists for the challenges of the 21st century.

During 1993 the Plynlimon experiment celebrated its 25th anniversary (the first meteorological readings having been made in 1968). With the bulk of the hydrological networks being commissioned between 1969 and 1975, Plynlimon is now the longest-running intensively monitored catchment experiment in Britain. It is probably only surpassed in world terms by the Coweeta and Hubbard Brook studies in the USA. As described in previous annual reports, the Plynlimon study has played a central role in demonstrating at a catchment scale the much higher evaporation losses from forest than from short grass vegetation.

In recent years the long data record available has also revealed that the absolute values of losses from both forest and grass have been declining: the amount of forest evaporation is now similar to that from grassland at the start of the experiment (grassland losses have also declined). This finding suggests that land-use effects may be matched in importance by climatic variability, posing fundamental questions about future losses. Will they

Figure 16 Afforestation at Llanbrynmair, Wales

continue to decline (assisted perhaps by anthropogenic factors, such as chemical pollution reducing plant transpiration rates in ways we do not yet understand), or will there be a reversal and a change to higher water use by vegetation? As well as such strategic considerations, the attractions of the intensively-monitored 'open air laboratory' at Plynlimon have encouraged recent investment by the NRA in studies of sediment outputs and hydrochemical changes associated with clear-felling and the start of the second forest rotation.

The Coalburn catchment experiment in northern England has also run for more than 25 years. This study monitors the change from rough grazing moorland to plantation forest, which is now at canopy closure. To mark this crucial period a thorough review of the data collected has been commissioned by a consortium of the NRA, Forestry Commission and North West Water plc. The findings have called into question many established views of the hydrological effects of forestry (such as lower floods and less erosion) by showing that pre-planting site preparation may have the opposite effects. Furthermore, far from being short-lived, some of these impacts (including flood peaks and baseflows) may persist at higher than pre-planting levels for up to one half of the duration of the forest rotation.

The Llanbrynmair catchments in mid-Wales are also approaching a crucial period. The initial effects of afforestation on water use, streamwater chemistry and sediment outputs have largely settled into new (although different) equilibria and the forest there will approach canopy closure in the next few years.

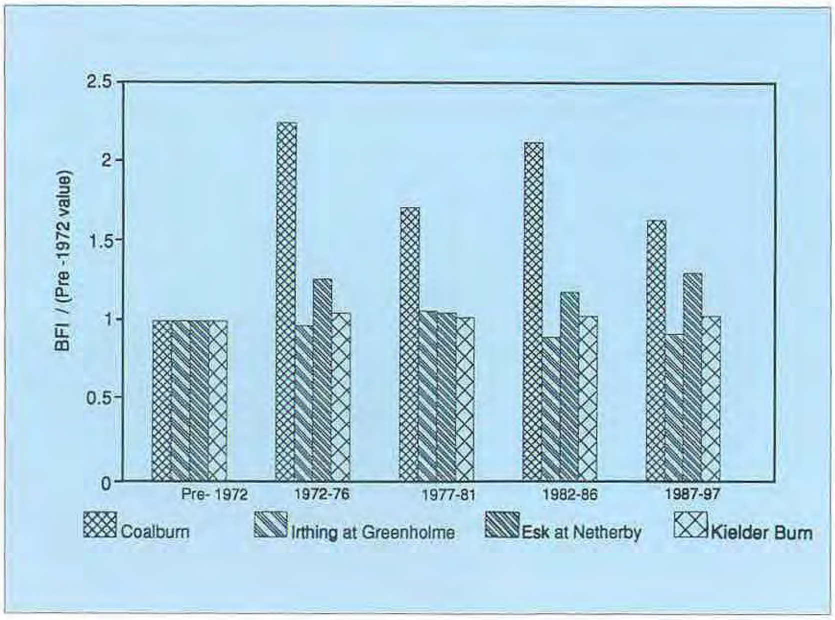


Figure 17 *Base flow index (BFI) for Coalburn and nearby catchmnts relative totheir pre-1972 values. The BFI for Coalburn doubled following its ploughing for forestry and remains high some 20 years later.*

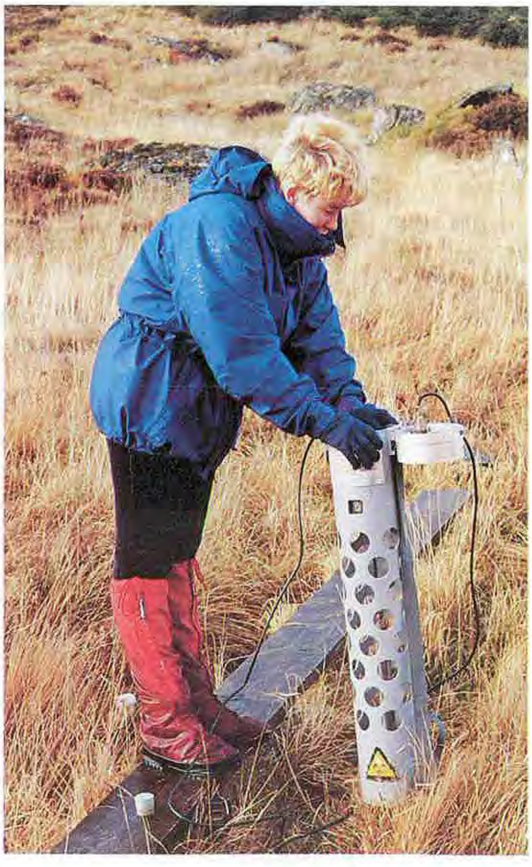


Figure 18 *Soil moisture data collection at Balquidder*

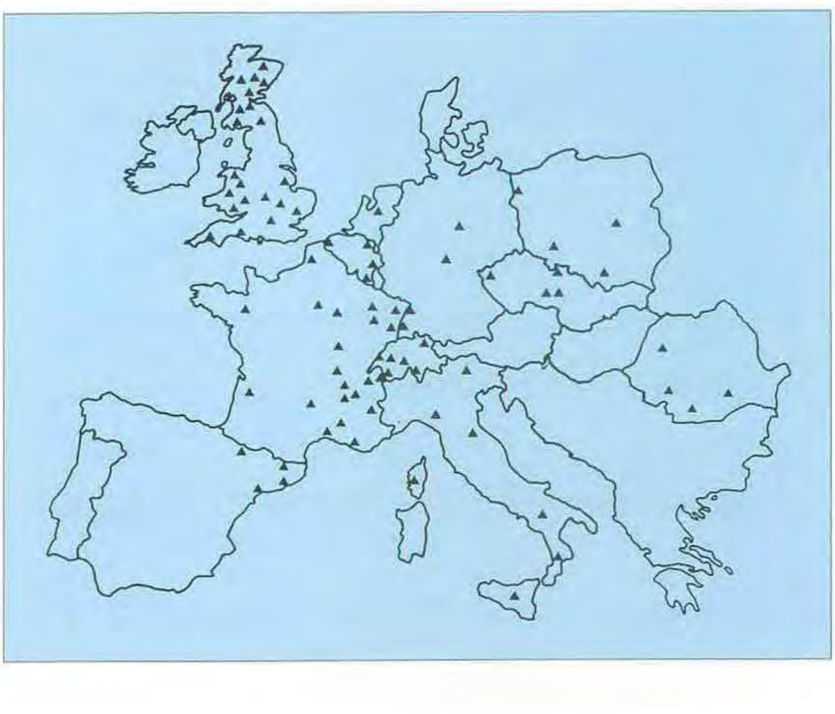
The Balquhidder catchments have completed ten years of continuous data collection and continue to produce useful information on the slightly different effects of land-use change which are found in the Scottish highlands.

ERB – International collaboration

The European Network of Experimental and Research Basins (ERB) was founded in 1986. Its aim is to foster international contacts between scientists concerned with catchment research, through meetings and data exchanges and the encouragement of joint research projects. The ERB Inventory provides a computer database of approximately 150 basins, including their physical characteristics, instrumentation, data, research aims and key publications. The Inventory can be accessed by member countries to obtain information about basins which fulfil certain criteria; for example, it was used in the FRIEND project to identify small research basins in northern and western Europe concerned with physical process studies of streamflow generation. Another study uses the network to investigate the effect of forestry on river flows.

During the year the Institute of Hydrology was the host organisation for the Fourth International Conference and General Assembly of the ERB. Attended by scientists from 14 countries in Europe and North America, the four-day meeting dealt with techniques of comparing and analysing basin data. Twenty-one papers from the Conference have been edited and published by the Institute as *No. 120* in its Report Series. They deal with topics such as measurement problems, techniques for distinguishing land-use change effects from climatic variability, the problem of transposing results from the small scale to larger areas and the use of models to predict the effects of future changes (or to 'hindcast' conditions back in time before the changes took place). The papers include practical examples of the application of these techniques, and the publication has therefore been proposed as a UK contribution to the World Meteorological Organisation's HOMS project (see Appendix 6).

Figure 19 *Location of ERB research catchments*



FRIEND in Europe and Africa

The FRIEND programme (Flow Regimes from International Experimental and Network Data) is an international collaborative venture to improve understanding of hydrological behaviour on a regional basis. Led by IH, FRIEND is a major contribution to UNESCO's current International Hydrological Programme IV and was recently designated Project 1.1 of IHP V for adoption by the Intergovernmental Council in February 1995.

Initiated in 1985, FRIEND originally involved 13 nations in Northern and Western Europe. Such has been the growth of interest in FRIEND that 17 countries actively participate now. Funding for the project is provided by NERC, the Department of the Environment, the Overseas Development Administration, the Commission of European Communities, the Norwegian National Committee for Hydrology and various universities and research institutes throughout Europe.

Research within European FRIEND is undertaken by five project groups. The Database group is responsible for maintaining and developing the European Water Archive. Based at Wallingford, the archive is the most comprehensive hydrological database in Europe, storing gauged daily flow data, instantaneous maxima, catchment characteristics and flow statistics for some 4000 gauging stations across the continent.

A Low Flows group works on regional low flow studies, modelling the effects of land-use change and groundwater abstraction on low flows, together with a hydrological classification of European soils. A third project deals with large-scale studies of flow regimes and has developed procedures for classifying river flow regimes and for mapping average annual runoff from digitised catchment boundaries. Techniques for extreme rainfall and flood runoff estimation and physical processes of streamflow generation are dealt with by the fourth and fifth project groups.

Some notable achievements of the research are

- the development of low flow estimation procedures at the regional and European scales;
- model simulation of the impact of afforestation on the low flow regime of European catchments;
- the calibration of groundwater models on selected basins to investigate the sensitivity of low flows to groundwater pumping and other factors;
- the definition of large-scale hydrometric regions;

- the review of flood estimation procedures for some European countries, and
- the production of an inventory of 50 small research basin studies in Europe.

The Institute of Hydrology has promoted the concept of FRIEND beyond Europe, in particular to the Southern African region. The Southern African FRIEND project promotes research into the spatial and temporal variability of floods and low flows in ten countries. The University of Dar Es Salaam in Tanzania acts as the project coordination centre. Financial support is provided by the UK Overseas Development Administration, the Irish Government (through the University of Galway), the Water Research Commission (South Africa) and the hydrological organisations of the participating countries. The project is aimed at establishing a common river flow database of gauged daily flow and flood event data for some 1000 sites. This has been facilitated by the supply of the Institute's HYDATA software package (for archiving, processing and analysing data) and by providing relevant training to staff in the participating countries. Computer-based GISs are being used to process gridded maps of climatic, soil and vegetation variables of the region.

The regional data set will be used to develop regional flood and low flow estimation procedures and to quantify hydrological variables at the sub-continental scale. On its completion in 1996 the project will produce practical design procedures for engineers and water resource planners, as well as covering scientific issues such as spatial coherence, probability of drought occurrences and the hydrological impact of land-use change.

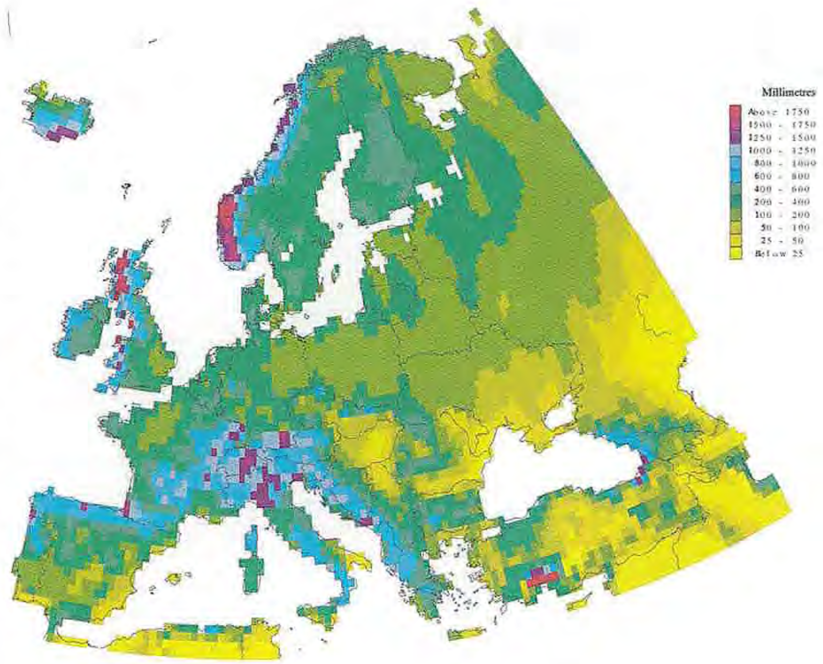


Figure 20 *Average annual runoff across western Europe*

Other FRIEND initiatives have been set up around the World. Countries of the Mediterranean region have set up a similar project, AMHY, and a new Western and Central Africa FRIEND project was launched in Burkina Faso in July. Further interest has also been shown by nations in the Hindu Kush / Himalayan region of Asia and by nations in South America.

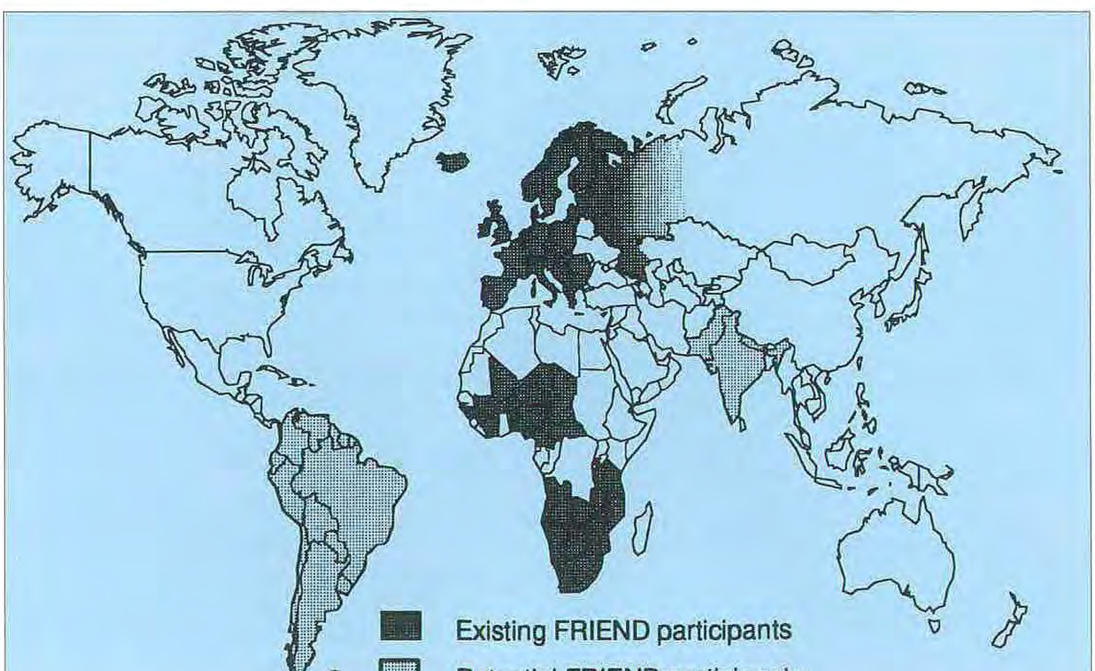


Figure 21 *World map showing areas of interest to the FRIEND project*

Agricultural pollution — prediction for water quality control

It is now difficult to find any river, lake or estuary in the UK unaltered by human activities. The need to grow crops, develop cities and dispose of industrial and urban waste has led to the inevitable deterioration of water quality over a long period of time. As rain falls on the land surface and moves over and through the ground, the rocks, soil and vegetation each contribute their own mixture of nutrients and other chemicals. Industry, farming and urbanisation also produce nutrients and other substances, including synthetic chemicals such as pesticides, which find their way directly or indirectly into rivers and groundwater. The inputs from agriculture are most difficult to manage and predict: they are applied widely across the landscape and washed insidiously into lowland streams and rivers.

Unlike upland streams, where the concentration of dissolved oxygen is mainly controlled by natural re-aeration brought about by steep gradients and uneven beds, in lowland rivers biochemical decay and respiration may become the dominant processes. Where effluents from agricultural sources with a high biochemical oxygen demand (BOD) enter a river, the dissolved oxygen concentration decreases immediately and continues to 'sag' downstream, recovering only slowly as the effluent is broken down and re-aeration occurs. Some organic effluents are particularly troublesome because of their high BOD as, for example, silage effluent which may have a value 200 times that of raw sewage.

Figure 22 *Laboratory analysis of pesticides in water samples*

Nitrates

Nutrients such as nitrates and phosphorus are important factors in the generation of algal blooms in lowland rivers and reservoirs. Nitrates in particular are receiving considerable attention because of the perceived health risks and the consequent EC directives regarding permissible levels in surface waters used for public supply. Nitrate concentrations have risen steadily since the 1940s reflecting increased cultivation of land, increased use of fertilizers and changes in cropping patterns. In the rivers, the nitrate content of land runoff may be augmented by that from more localised sources such as sewage discharges, intensive farm units and silage liquor stores. Each catchment has a unique combination of local and diffuse sources of nitrate and the association between river discharge and contaminant concentration can be very complex. Scientifically designed monitoring networks and sampling programmes are essential to permit total contaminant loads to be assessed with sufficient accuracy to identify significant changes through time.

New mathematical modelling techniques have been developed at IH to predict nitrogen movement through catchments. These techniques allow for the vertical and horizontal movement of water through catchments and they are coupled with the complex equations describing nitrogen processes in catchments. The models comprise two components: one describes water and nitrate movement, the other transformations of nitrogen compounds.

The vertical soil leaching component in each grid square uses the mobile/immobile water concept of the Rothamsted SLIM model; nitrogen transformations are described using associated routines. This provides daily estimates of the leaching of nitrate below the root zone. Once below the root zone, the main chemical processes affecting nitrogen species are regarded as complete, with the exception of denitrification. The remaining part of the model distributes the vertical leaching estimated by SLIM over the catchment, routing water and nitrate laterally through soil, rock and streams to the catchment outlet. A continuous estimate of discharge and nitrate concentrations is provided at the catchment outlet and elsewhere. Because the causal mechanism of leaching is followed through, the influence of changes, in inputs or catchment, on catchment nitrogen outputs can be estimated. These models have been applied on a small plot scale at Brimstone Farm and at a large catchment scale at Bourne Brook near Coventry.

The 43 km^2 Bourne Brook catchment feeds a public supply reservoir. Because nitrate concentrations in the stream were high, the catchment was designated a Nitrate Advisory Area. Substantial reserves of groundwater in sandstones in the catchment maintain base flows, but these reserves have become contaminated by nitrate, although the greatest nitrate concentrations are associated with an autumn flush of field drainage water to the stream.

The leaching model for Bourne Brook uses, as far as possible, readily available survey information on catchment structure and inputs of water and nitrogen over a 200 m grid. Structural information includes topography, geology, soils, stream configuration and patterns of land use, while inputs are taken from meteorological and farm survey data. These form a database which may be modified as appropriate when using the model at other sites.

Measured data from Brimstone Farm covering the yearly period August 1985/86 are currently being used to test the ability of the model to simulate leaching over individual storm events and through the year.

Pesticides

Pesticides are undesirable pollutants of river and groundwater resources because of their potential harm to human health and damaging impacts on the environment. Precisely how pesticides reach rivers or groundwater as a result of normal agricultural practice is an important question for environmental scientists.

As part of the NERC/AFRC special initiative on pollutant transport in soils and rocks, the Institute is collaborating with the Soil Survey and Land Research Centre (SSLRC) and Horticulture Research International (HRI) to study pesticide transport in heavy clay soils. The work is based on two field sites, one at Temple Balsall in Warwickshire, managed by SSLRC, and one at Wytham, Oxfordshire, managed by IH. At Wytham, the movement of the herbicide isoproturon, which has been applied to winter wheat, is being studied in a mole-drained field.

Using experience gained in previous pesticide transport work at the ADAS Rosemaund Experimental Husbandry Farm in Herefordshire, a variety of instruments have been installed, including pressure-transducer tensiometers and the soil moisture capacitance probe. Equipment has been specially developed to measure flows and to sample water moving in both tile and mole drains and in overland flow on the soil surface. To complement the field studies, soil columns from the field are being tested in the laboratory to examine the detailed relationship between worm burrows as flow paths and the surrounding matrix.

At first glance, a clay soil with good adsorptive capacities for organic molecules and with a low matrix hydraulic conductivity would appear to pose little threat to the surrounding watercourses. However, preferential flow mechanisms predominate in this type of soil, such that rainwater interacts with only the top few centimetres before escaping down macropores or running down the slope as overland flow. This is of particular importance,

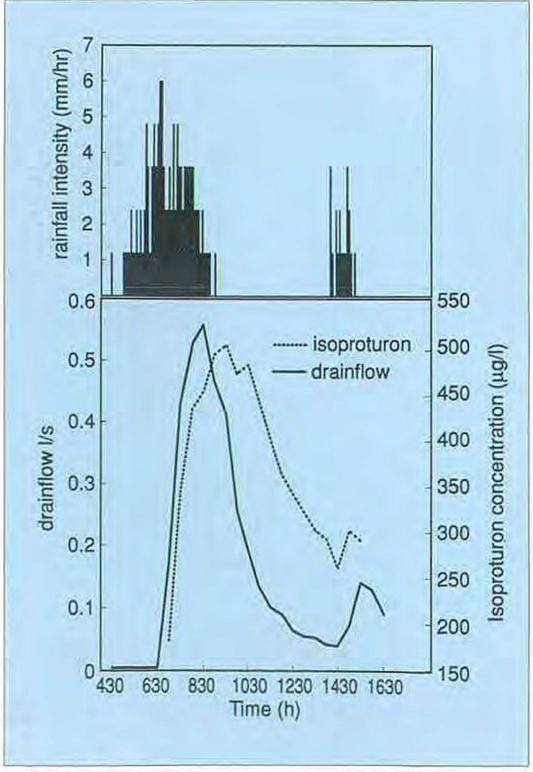


Figure 23 *Relationship between rainfall (top), drain flow and isoproturon concentration, 50 days after the pesticide was applied*

since in these soils the majority of the pesticide is found in the top few centimetres of the soil and may interact with these flow mechanisms.

Figure 23 illustrates the interaction of rainfall intensity with drainflow and isoproturon concentration. Drainflow is seen to commence when the soil at or above 10 cm is saturated, even when the soil below that depth is unsaturated. This is interpreted as water entering the drainage system directly from above via macropores which function when the topsoil is saturated. The potential for significant contamination of nearby water courses through such vertical by-pass flow in a mole-drained clay soil can be seen from the high isoproturon concentration in the tile drain (500 $\mu g l^{-1}$ peak, equivalent to a loss of 1.5% of that available in the soil) during the rainfall event.

The Institute is now also involved in studying the microbiological component responsible for degradation of the pesticide. Figure 25 illustrates the much reduced microbial potential to degrade the pesticide below the top soil. This is an area of concern, particularly with regard to groundwater quality, as pesticides may reach the groundwater and then persist there for long periods.

Having formed a qualitative description of the processes which control water and pesticide movement in these types of soils, a mathematical model can be developed. Field sites or laboratory experiments can then be simulated and the model output compared with the experimental observations. Models of solute transport in soils have generally assumed percolation of water through the soil matrix and are based on Darcy's law. This law, combined with the continuity equation, leads to the Richard's equation solution for solute transport. Using such models has led to predictions of very slow movement of pesticides to depth with

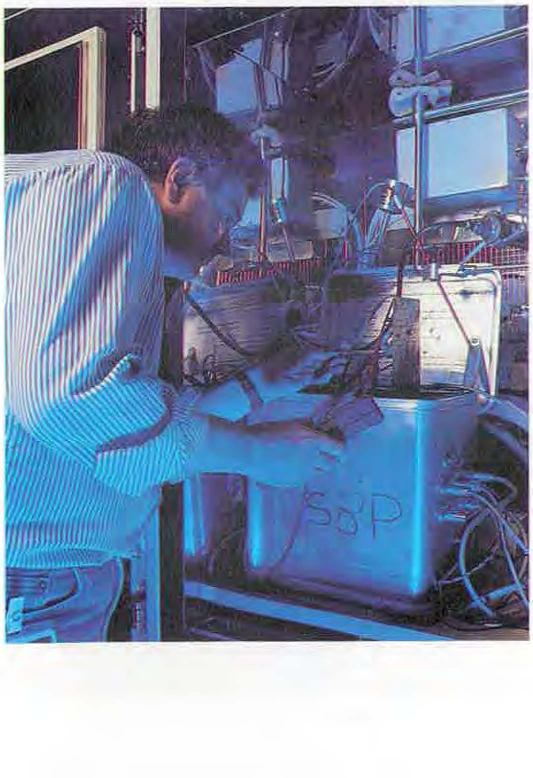


Figure 24 Calibration of field instruments in a temperature-controlled cabinet

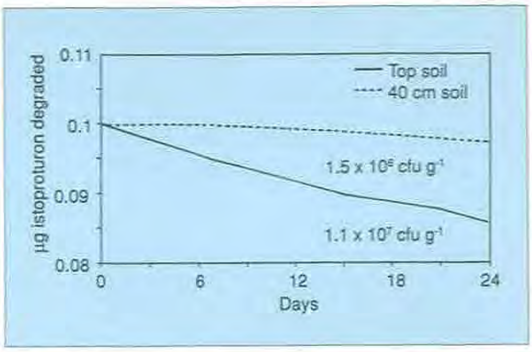


Figure 25 *Degradation of ^{14}C-isoproturon in Wytham soil*

the bulk of the pesticide confined to the top 20 cm or so of the soil. Little or no pesticide is predicted to reach tile drains and hence surface waters. This prediction is clearly not correct for the clay soils encountered at Wytham and Rosemaund. Modifying the models to include by-pass route mechanisms has already been tried at Rosemaund with some success and will be carried forward in the work at Wytham.

Reservoir control of agricultural pollutants

Finally, whilst models can predict inputs from agriculture to rivers there is still the problem of how to cope with pollutants once they enter the water supply system. In the case of pesticides, they may be removed at treatment plants using carbon filters; similarly nitrates can be removed by denitrification. Both processes are expensive however, and quite often our water resource system can be controlled and manipulated to reduce the problem.

As an example of this, consider a reservoir receiving water high in nitrates. By increasing the retention time of water in reservoirs the nitrogen levels will decline as natural denitrification occurs. To investigate the interactions involved, a dynamic flow and quality model for reservoirs has been developed which allows for given inflow and outflow pumping rates and concentrations, and accounts for the denitrification process. Figure 26 shows the results of applying the model to Farmoor reservoir near Oxford over about 12 years of weekly data. In general, an excellent fit with the measured values of nitrate concentration is obtained.

Also presented in Figure 26 are the volume of water in the reservoir and the mean retention period. The reservoir is kept full for much of the time, especially in the early years of operation, although droughts in 1971, 1973 and 1975-76 show reservoir volumes decreasing. The mean retention period is 24 weeks in the first six years of operation, but in the later years this falls to about ten weeks. This period corresponds to increasing nitrate levels in the reservoir, which appear to be due to a combination of higher river nitrate concentrations and decreased reservoir retention periods.

It is also possible to use the model to determine reservoir response to a variety of hypothetical or predicted river nitrate patterns. An example of such a predictive exercise is shown in Figure 27 where it has been assumed that the reservoir has a retention period of 100 days and the regular annual nitrate cycle has a constant maximum of 12 mgl^{-1} during the winter quarter and a constant minimum of 6 mgl^{-1} during the summer quarter.

The reservoir is assumed to be well-mixed, and its predicted nitrate concentration with no denitrification matches the average in the river, as expected. However, the maximum nitrate concentration is lower than in the river, and is delayed for two months; this illustrates the protection afforded by bank-side storage derived purely from hydraulic effects.

The lower two graphs in Figure 27 shows what might happen if the reservoirs exhibited denitrification. The middle graph is for an increased reservoir depth (20 m): denitrification removes 0.9 mgl^{-1} nitrate-N from the peak concentration. In the bottom graph (10 m depth) 1.5 mgl^{-1} of nitrate-N is removed. For a given retention period, shallower reservoirs or lakes remove nitrate more efficiently. From such studies optimal conditions for denitrification can be identified:

- Shallow water (maximum ratio of surface area of mud to water volume);
- No stratification (warmer water against the sediment);
- Long retention period (maximum time for denitrification to occur);
- High primary production (concomitant low population of zooplankton); and
- No exposure of sediments during drawdown.

Many of these optimal conditions cannot be sustained because of conflicting water resource requirements: reservoirs need to be maintained at the maximum level for adequate water supply. However, the most important condition, maximising retention period, is consistent with maintaining reservoirs near full, and will meet both objectives. Unfortunately, demands on water are such that major reservoir drawdowns are anticipated in dry summers, and the best strategy is to avoid using poor quality river water which is high in nitrate. This could be achieved by avoiding the first flush of nitrates following a relatively dry spell. Thus a model has been useful for determining optimal conditions for reservoir management and could be used for real-time operational purposes to minimise nitrate concentrations.

There is no doubt that agricultural land-use change will affect upland and lowland water quantity and quality as well as groundwater systems. The processes controlling transport and distribution of pollutants in river and groundwater systems are well-known. Models are being used increasingly to assess the myriad of interactions between processes, chemicals and hydrology. The NERC/AFRC initiative on hydrochemical flow paths will go some way to resolving some of the problems but new ones will inevitably arise, especially as land-use change speeds up in lowland Britain.

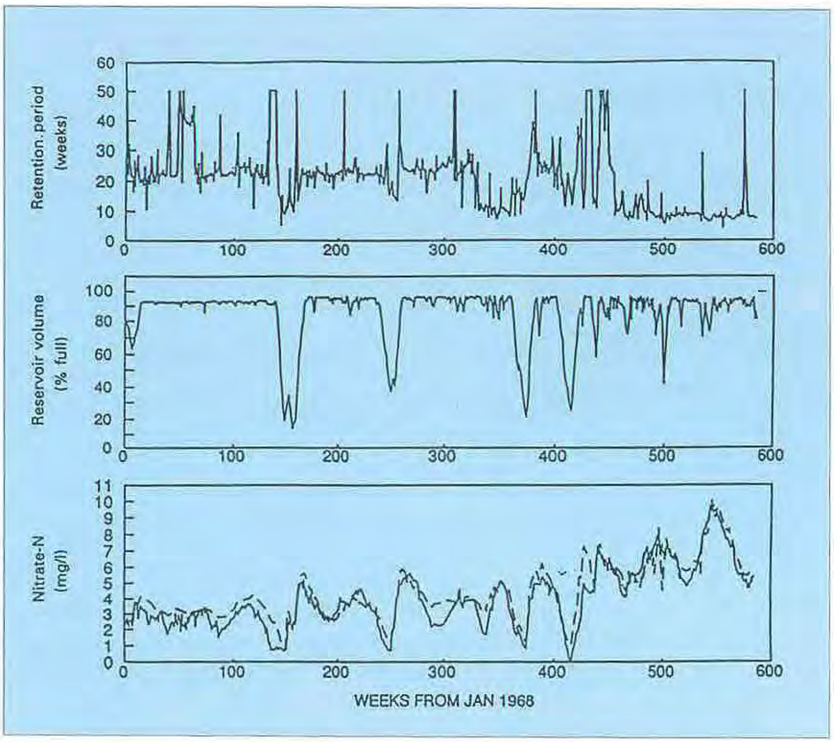


Figure 26 *Nitrate, volume and retention period simulations, Farmoor Reservoir, Oxfordshire*

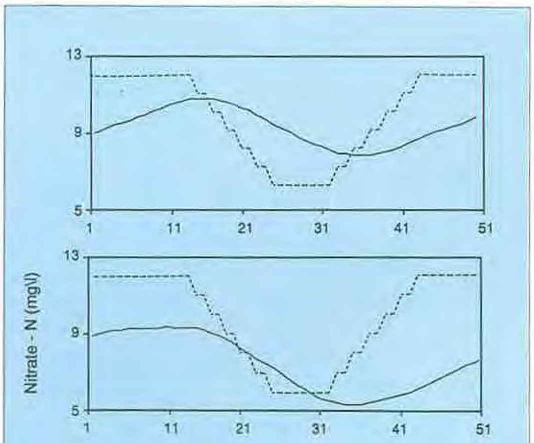


Figure 27 *Simulated reservoir response for different values of depth and denitrification*

The critical loads concept for pollution control

Acidification of soils and fresh waters is now known to occur in areas of north-west Europe, Scandinavia and North America as a response to deposition of nitrogen and sulphur compounds. The biological consequences are reduction in fish populations, changes in invertebrate and diatom communities and damage to forests. The source of these pollutants is also well-known: oxides of sulphur from combustion of fossil fuels (predominantly from power generation plants), oxides of nitrogen from industrial and road traffic emissions, and reduced nitrogen (ammonia) from agricultural areas.

Much is now understood about the process of acidification and the controls on both the degree of damage suffered and the spatial extent and occurrence of the damage. In short, sulphur and nitrogen compounds leaving a catchment system — in the form of mobile anions, negatively-charged ions — are charge-balanced by positively-charged ions (cations) derived from weathering and soil ion-exchange processes within the catchment.

In a catchment where calcareous rocks occur, or where soils and bedrock weather quickly, there is a huge store of available base cations (calcium, magnesium, sodium, potassium) to balance the mobile anions and therefore no net acidification occurs in the long term (although short-term acidic pulses may occur in streams driven by rain storms or snowmelt events). In catchments where base cations are only slowly supplied by weathering processes, or where there has been an acute input of mobile anions, the base cation store is quickly depleted and acidic cations (hydrogen and aluminium) are released, causing a net acidification (reduction in alkalinity) of the soil-surface water system.

Identifying the link between fossil fuel burning, acidic emissions, acidic deposition, soil and freshwater acidification and adverse biological impacts has led to attempts to reduce emissions at source. The fact that atmospheric pollution can travel large distances, across national boundaries, has necessitated emissions control within the framework of international agreement. To this end the United Nations Economic Commission for Europe (UNECE) adopted the Convention on Long Range Transboundary Air Pollution (LRTAP) in 1979. Under this convention, a protocol to reduce sulphur emissions by 30% from their 1980 levels was adopted by several countries, the so-called "30% club", in 1985. Sulphur dioxide emissions have in fact declined by about 30% since 1980, largely as a consequence of the closure of small coal-fired power stations in the early 1980s and the general decline in industrial output at the end of the decade.

Further to this UNECE agreement, the European Community adopted the Large Combustion Plant Directive in 1987, committing member states to reduce emissions by 60% by the year 2003. A further protocol concerned the control of emissions of nitrogen oxides or their transboundary fluxes: adopted by the UNECE in 1988 (this time signed and ratified by the UK), it committed countries to freeze their NO_x emissions at 1987 levels by 1994.

All these agreements are soon to be re-negotiated. The EC SO_2 agreement is due to be revised in 1994 and the UNECE SO_2 protocol in 1993. In negotiating the new protocol it has been recognised that emission reductions need to be targeted to produce deposition reductions in specific areas, given the controls on the acidification process outlined earlier: "blanket" reductions are neither cost effective nor environmentally effective. To assess spatially distributed emissions reduction, targeted at the most heavily impacted ecosystem, the concept of "critical loads" has been formulated. This provides the scientific basis for the negotiation of the new emissions reduction protocol.

The critical load of sulphur and nitrogen for freshwater is defined as "the highest load that will not lead in the long term (within 50 years) to harmful effects on biological systems". Similarly the critical load for soil is defined as "the highest deposition of acidifying compounds that will not cause chemical changes in soil leading to long-term harmful effects on ecosystem structure and function". If the goal is to protect soils over very long time periods (>1000 years), then the critical load approaches zero. A more practical limit is that acid deposition shall not lead to unacceptable soil acidification over 50 to 100 years.

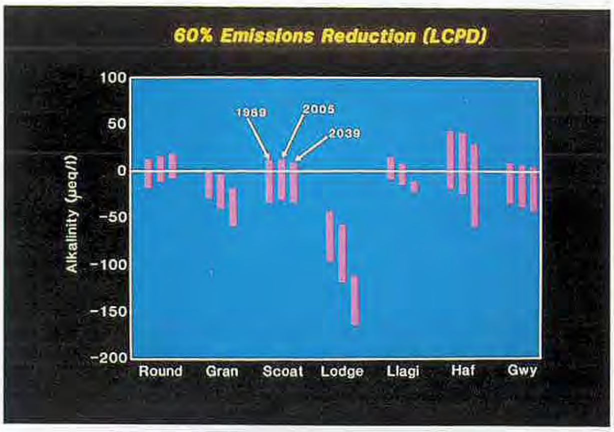


Figure 28 *Water quality response to the 60% emissions reduction proposed in the Large Combustion Plant Directive (LCPD)*

Critical loads for water and soil are only of interest, however, when defined with the purpose of protecting a sensitive receptor. For example, water acidification can lead to decline or disappearance of natural fish populations and soil acidification affects biological organisms in terrestrial ecosystems such as trees. Criteria for "unacceptable change" are set in relation to effects on terrestrial and aquatic organisms.

With respect to damage to terrestrial vegetation, common criteria include the concentration of inorganic aluminium in soil solution and the ionic ratio of aluminium to calcium in soil solution, where the soil solution at rooting depth (0-50 cm) is of primary interest. With respect to aquatic organisms, common criteria are that the runoff water should have positive alkalinity and a concentration of labile inorganic aluminium less than 50 g l^{-1}.

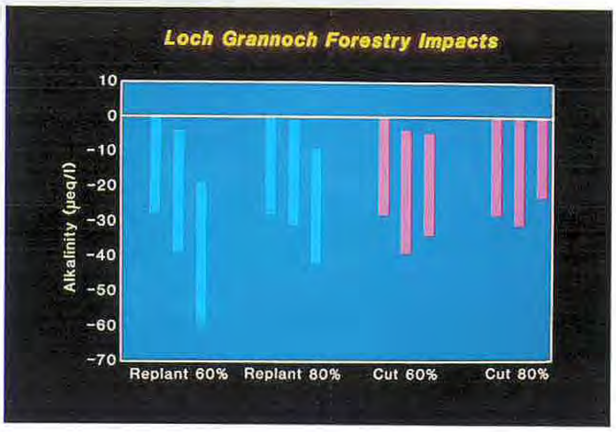


Figure 29 *Water quality response at Loch Grannoch to future forestry policy*

The purpose of determining critical loads is to set goals for future deposition of acidifying compounds such that the environment is protected. Critical loads are determined separately for soils and surface waters and will differ for a given area as well as from site-to-site, depending upon the inherent sensitivity of the natural environment. In practice, the critical load for soils at a given site may be greater or lower than the critical load for water. Because the goal is to protect the whole environment, the critical load is taken to be the lower of the two. In other words, if the water is inherently more sensitive than the forests, the critical load for water will be lower than that for forests, and is taken to be the critical load for the whole environment.

Critical load maps for sulphur and nitrogen are now well established for soils and waters within the UK. Using information on current deposition fields together with future projections based on assumed emissions reduction scenarios, present and future critical load exceedances can be calculated. This enables reductions to be targeted at specific emitters thereby optimising the benefit to the most sensitive areas.

The empirical approach to critical load calculation, based on the long-term weathering rate at a site, is time independent, i.e. steady-state conditions are assumed. It also assumes that the rate of recovery at a site is unimportant, even over very long time frames (>100 years) and — more crucially — that the site is not only capable of recovering to a target chemistry level but also that prior to the onset of acidification the water chemistry was equivalent to or less acidic than that level. Furthermore, the influence of the catchment soils, in particular their ability to adsorb and desorb ions through time, is only implicitly included in the empirical model which assumes that in the very long, or equilibrium, time-scale the soil acidification process is completely reversible. In fact, soil chemical processes may mitigate or delay acidification.

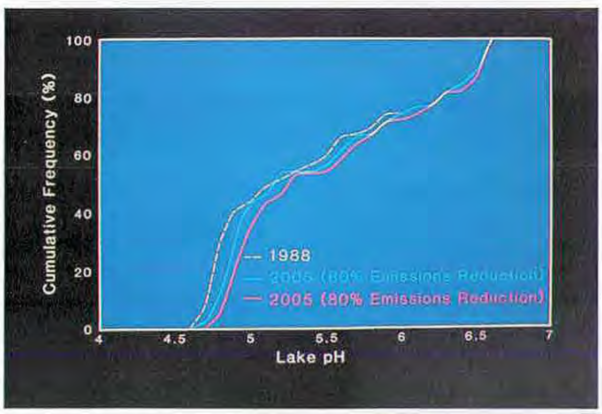
An alternative approach at IH has been to use dynamic modelling to account for changes over time such as the depletion of element pools in soils. The dynamic catchment-based long-term soil and water acidification model MAGIC (Model of Acidification of Groundwaters In Catchments) has been used in several ways:

- to identify the regional characteristics that determine critical and target loads;
- to determine the time dimension between achieving critical loads and ecosystem recovery;
- to determine the consequences, in terms of surface water and soil chemistry, of not achieving a critical load;
- to examine the effect of land-use change, in particular forestry practice, on critical loads;
- to determine the interaction between nitrogen and sulphur in the context of critical loads for total acidic deposition.

The strength of these dynamic model applications in an applied sense is in answering key policy questions such as: *What degree of soil and water recovery, in time and space, can we expect from a given emissions reduction strategy?* and, *What level of emissions reduction is necessary to achieve a given level of soil and water recovery within a given time scale?*

In addressing these questions, the MAGIC model has been calibrated to 16 of the 22 sites in the UK Acid Waters Monitoring Network (UKAWMN) for which IH acts as the central repository for chemical data. Those sites excluded currently lack sufficiently detailed soil chemical data. The AWMN sites represent a range of acid impaction and sulphur deposition flux across the UK and calculated critical loads are currently exceeded at six sites. At these sites the Large Combustion Plant Directive (LCPD) emission strategy has been assessed to examine future water quality response. The model has been applied assuming that the LCPD emissions reductions are achieved by 2005 and that emissions are held constant thereafter until 2039.

Taking positive alkalinity and pH greater than 5.5 to generally reflect thresholds for the survival of a viable brown trout population, the model predictions for 2005 and 2039, compared to present day observations, show a consistent picture. The reduction in sulphur deposition to these catchments in response to the LCPD emissions reduction strategy is *not* sufficient to improve the water chemistry status of these acid impacted sites significantly.



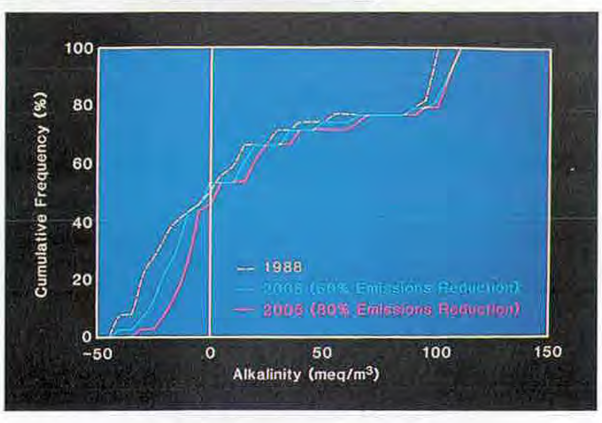


Figure 30 *Lake pH and alkalinity response to the LCPD emissions strategy, as wellas to a more optimistic 80% emissions reduction, for 39 lakes in Galloway, south-west Scotland*

At the Round Loch of Glenhead (south-west Scotland) the LCPD scenario is just sufficient to achieve an alkalinity of zero by 2039 but pH improves only slightly to 5.2. At Llyn Llagi (North Wales), the deposition reduction is too small to even halt the decrease in alkalinity which becomes negative by 2039 although pH remains constant at 5.1. At Scoat Tarn (Lake District), on the other hand, the alkalinity increases in response to the decrease in deposition to 2005 but this is only temporary and a further decline to beyond the present day level occurs. The deposition reduction predicted from the LCPD is clearly not sufficient at Old Lodge (South Downs) and extreme acidification continues throughout the simulation period.

This dynamic modelling analysis indicates that recovery depends on the timescale over which the emissions reductions are made. It is also clear that whilst the critical load may be achieved at a given site within a given time frame, the water chemistry may at that time still be unsuitable for aquatic organisms because of the inherent time lags in the catchment system which slow the rate of recovery of surface water chemistry.

Future land use policy within a catchment is another important factor in the process of reversing acidification. In this respect, the role of trees in the critical loads concept requires careful consideration. As well as being sensitive receptors for which critical loads need to be determined, they play a crucial role in the soil and water acidification process by uptake of base cations for growth, changing hydrological behaviour, and by scavenging pollutants from the atmosphere thereby increasing the deposition.

The model application at Afon Hafren (Mid Wales) and Loch Grannoch (south-west Scotland) show a more complicated situation which occurs when considering the issue of future afforestation policy. In general, two future land-use scenarios are possible: forest felled and replanted and forest felled without replanting. In both example catchments the second option produces the better prediction of water chemistry recovery.

Clearly, the calculation of critical loads for soil and freshwaters in areas where plantation forestry is a major land use require consideration of these impacts. It is ironic that the areas where commercial afforestation is concentrated coincide with the acid-sensitive upland terrain which receives high sulphur loads and where current critical loads are exceeded. The results underline the need to take land management into consideration in association with sulphur deposition strategies.

A further modelling exercise has centred on a regional MAGIC model application to 39 lakes in the Galloway region of south-west Scotland. The lakes are confined within an area of about 120 km² representing some 16 10 km squares delineated in the UK freshwater critical loads mapping exercise. This area has been identified as having a large proportion of acidified surface waters following decades of acidic deposition. Many of the lakes and streams are susceptible to acidic deposition because of the relatively slow weathering and low acid neutralisation capacity of the bedrock, thin and acidic soils and extensive afforestation. Other fresh waters in the area, lying predominantly on less sensitive geology, have a high positive alkalinity and are not currently acidified. This wide range of sensitivity to acidic deposition, with respect to both soils and waters, presents considerable problems for quantifying regional critical and target loads.

To address this issue, data from these lakes, sampled in 1979 and again in 1988, were used in conjunction with detailed soil data obtained from the Macaulay Land Use Research Institute (MLURI) and forest management history from the Forestry Commission, to formulate a regional application of the MAGIC model. Lake alkalinity and pH response to the LCPD emissions strategy and a more optimistic 80% emissions reduction strategy were assessed using deposition data from the atmospheric transport model based at the University of Hull. The water chemistry simulations suggest that acidified waters with negative alkalinities in the region will recover only marginally in response to the LCPD scenario by the year 2005 (Figure 30) and the total percentage of lakes with negative alkalinity will remain roughly the same.

The location of these lake sites which require a much more dramatic decrease in emissions is determined by the extent of the underlying granitic geology. At these sites perhaps the question is whether other mitigation techniques, such as terrestrial source area liming, might be a cost-effective supplement to the emissions reduction programme. Clearly, the use of dynamic acidification models provides a valuable insight into the environmental effectiveness of proposed sulphur reductions.

A further development of the dynamic modelling approach is now under way to assess the influence of nitrogen dynamics in the context of critical loads for total acidity and given the present and future commitments to nitrogen emissions protocols. In general terms we know that an increase in nitrate leaching from a catchment may occur as a result of increased nitrate deposition, decreased plant uptake of nitrate (perhaps due to sulphur induced stress on the organisms), or through a change in climatic conditions leading to increased mineralisation of nitrogen in the soil. As a "mobile anion", if nitrate concentration increases in surface waters, without any concomitant decrease in sulphur concentrations, the total anion load will increase, resulting in decreases in pH and alkalinity.

Taking this argument further, it is inappropriate to consider critical loads for sulphur and nitrogen independently, since the level of either cannot be set without considering the other. The model emphasises that specification of a critical load for sulphur in the absence of knowledge of how the nitrogen dynamics within the catchment system might change in the future is inappropriate. The current MAGIC model can be used to indicate the "trade off" between the two critical loads, that is, lower sulphur deposition is required to maintain alkalinity zero in the light of increased surface water nitrate concentrations. A task for the future is to develop a long-term dynamic model for nitrogen which incorporates the major processes determining catchment nitrogen leaching, coupled to the existing sulphur model, so that surface water chemistry predictions can be made in response to a range of total acidity emissions reduction strategies.

Figure 31 *Upland lakes like this one in Galloway are susceptible to acidic deposition and have been the focus for a mathematical modelling exercise.*

Soil — the evasive link

The distinguished soil physicist Daniel Hillel defined the soil as "a natural body engaged in dynamic interactions with the atmosphere above and the strata beneath". These interactions form an integral part of the hydrological cycle, that never-ending process of water exchange between the earth and the atmosphere.

On land the soil plays an essential role within this cycle. It is the soil together with its vegetation cover which controls the partitioning of rainfall into surface and sub-surface flow. It is at the soil surface that water infiltrating the soil is taken into temporary storage and then routed either upward by evaporation or transpiration to the atmosphere, downward as deep drainage to the water table, or laterally as throughflow at shallow depth. In this way soil provides the link for the transfer of water between atmosphere and earth.

This link is evasive because the processes in the soil cannot be readily observed and also because the soil may be very heterogenous. Its hydraulic and physical properties may differ significantly both horizontally and vertically over distances of a few metres.

There can also be a change of properties with time, in response to changing land use. Slope, microtopography and vegetation cover — all of which play a role in the partitioning process— are also spatially variable. This means that the processes of water transfer through the system at any particular place or time are difficult to predict and even more difficult to quantify. However, techniques and instruments exist, and are being developed, which have allowed us a better insight into these processes, making this hydrologically important link less evasive.

Because it is such a vital element of the hydrological cycle, the function of the soil as a barrier, store or conduit for water has for many years formed a recurrent theme throughout a wide range of the Institute of Hydrology's work.

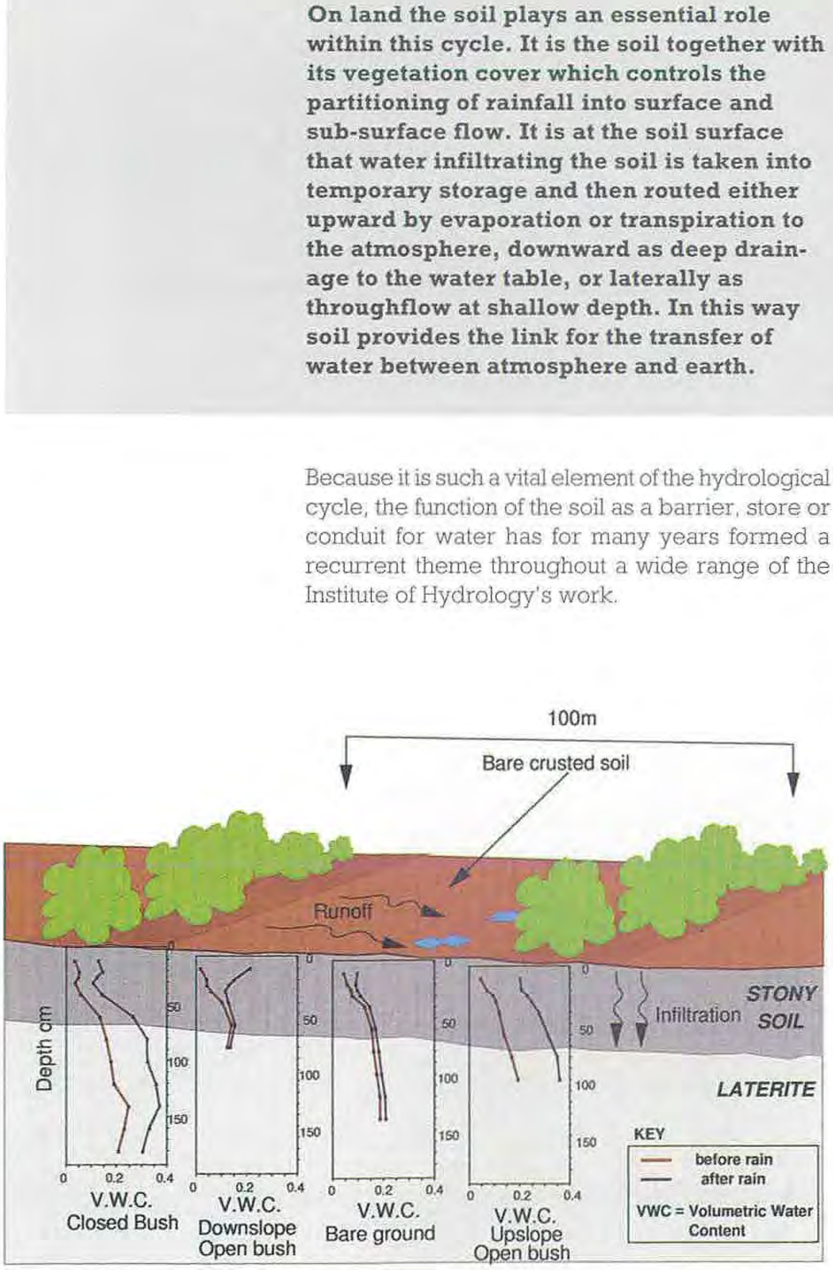


Figure 32 *As a result of runoff concentration, the amount of infiltration taking place beneath the vegetation can be between two and six times greater than the rainfall.*

Differential recharge

The theme is well represented by two groundwater recharge studies in semi-arid Africa. The first is in Niger, where the Semi-Arid Groundwater Recharge study (SAGRE) is focused on the spatial distribution and quantification of the recharge process. The second is in Zimbabwe examining the way in which changing land use can modify significantly the rate of recharge. In semi-arid Africa groundwater is a vital, life-giving resource, and the degree to which it is replenished seasonally determines the amount available for sustainable long-term exploitation. One of the more important controls on the level of this replenishment is the nature of the soil and the processes that take place within and upon it.

In the Sahel region of Niger, where rainfall is low and there is a thick unsaturated zone through which recharge has to pass, processes which concentrate the infiltration and locally increase recharge to the soil are very important. In this region the natural woodland vegetation, known as "Tiger Bush", grows in strips, separated by areas of bare ground. Over bare regions the impact of high intensity rainstorms has created a poorly permeable crust on the soil surface. This impedes infiltration and generates run-off into adjacent vegetation strips where it temporarily ponds and then infiltrates. This is illustrated by the soil moisture data in Figure 32,

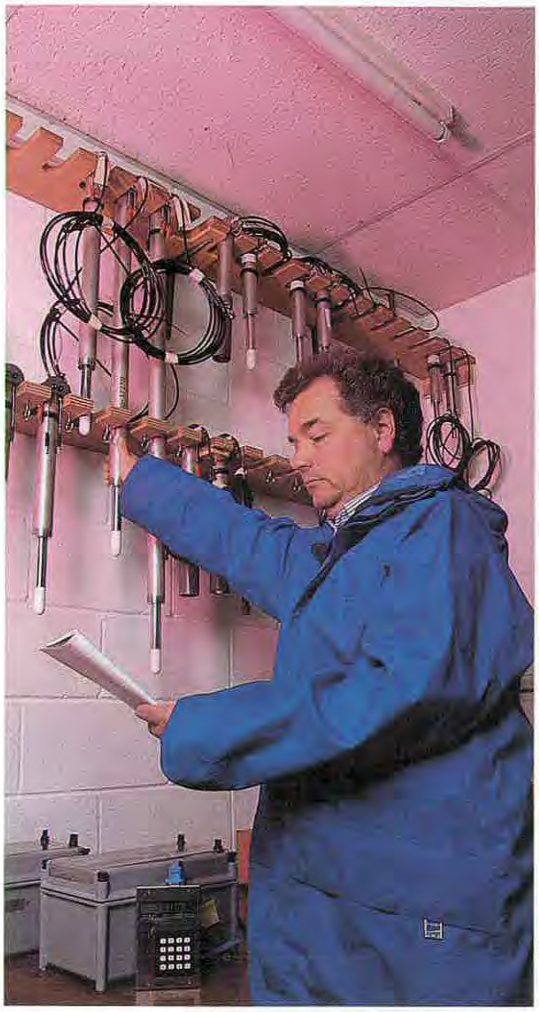


Figure 33 *Selecting tensiometers for use in the field*

where the difference in seasonal soil water storage change below bare and vegetated ground can be seen clearly. The effect of the natural water harvesting mechanism is to concentrate infiltration into the areas where it is needed to ensure the survival of the vegetation.

Although the vegetation uses much of the water fed to it, the likelihood of groundwater recharge is greatly enhanced in these areas, particularly at times of above average rainfall when excess water over and above the demands of evaporation and transpiration is made available.

Evidence is accumulating in the same region of the Sahel to show that there can also be substantial redistribution of rainfall at the soil surface within millet fields. Concentration of rainfall within micro-topographic depressions can lead to a threefold increase of storage within the soil profile compared to adjacent high areas. Studies have shown that much of this extra infiltration contributes to groundwater recharge and not to increased evaporation. From the point of view of aquifer replenishment this concentration mechanism is of the utmost importance, particularly since millet fields cover considerable areas in the region. Surface runoff ultimately reaches ephemeral stream channels and these may also be important foci of groundwater recharge.

Land-use change

The measurement and prediction of the effects of land use change on aquifer recharge and on catchment water yield and response are recurring questions posed to hydrologists. Large scale changes of vegetation cover modify the amounts of interception and of evapotranspiration and hence influence deep drainage (aquifer recharge) and catchment yield. The change in the depth of the soil profile accessible to the roots of the replacement vegetation is one of the main influences on evapotranspiration.

Modification of the hydraulic properties of the soil (particularly those of the immediate surface layer) can also result from changing land use through, for example, changed agronomic practice, soil degradation, or land drainage. These changes will modify the way that the rainfall is partitioned into surface runoff, throughflow, or deep drainage and therefore alter the hydrological response of the catchment area. How catchment behaviour will be altered following land use change will depend on which processes are most affected by the change, and in which direction they are affected. A sound understanding of the processes of water movement through soils is clearly essential to allow the effects of land use change to be modelled and predicted and to extrapolate local results to other areas.

In this context the Institute is carrying out a water balance study of a small, degraded catchment in an area of south-east Zimbabwe on a basement of extremely old crystalline rocks. The central objective is to establish the impact of land-use change on the hydrological processes operating in the catchment, with particular attention to groundwater recharge. Under existing degraded conditions the exposed soils of the study area are prone to crusting and generate significant amounts of surface runoff. The result is that the opportunity for direct recharge to take place through the soil and weathered rock is reduced significantly. Instead, points of recharge tend to be restricted to areas where infiltration may be concentrated such as the lower flanks of the largely bare rock hill slopes which border the agricultural areas, along the beds of ephemeral streams and where water can pond behind contour bunds in ploughed fields. The importance of these areas to the overall recharge is being investigated.

In the same area of Zimbabwe, the effectiveness of collector wells for domestic water supply and for limited-scale irrigation is being investigated jointly by the Institute and the British Geological Survey (BGS) in a project funded by the ODA.

Figure 34 A market garden irrigated from a collector-well at a village in Zimbabwe which continued to supply fresh vegetables during the recent prolonged drought in southern Africa

These are conventional wells, but with drill holes inserted radially and horizontally into the walls below the water table to help increase the sustainable yield in what are poorly-permeable aquifers. Results from the Institute's research will go some way to assessing the extent of and recharge to these limited aquifers and hence a measure of their sustainability.

The influence of major land-use change on global climate is of major concern, particularly the effects of rain forest clearance. The Institute is at the forefront of this research through its leading role in the ODA-funded Anglo Brazilian Climate Observation Study (ABRACOS) project. Results from the first field site in central Amazonia, near Manaus, have already shown that the forest uses significantly more water from the soil in the dry season than does the pasture vegetation which replaces it after clearance. Soil water abstraction from the upper metre of the soil was almost identical under forest and pasture, but the forest used about 40 mm more water, half as much again, from the second metre of the soil than the pasture and also exploited soil water to at least 3.6 m depth. The lower evapotranspiration from the pasture areas results in more of the incident radiation being converted into sensible heat, which has a strong influence on the development of the atmospheric boundary layer. This is the layer of air up to 3 km thick immediately above the Earth's surface and is where the general circulation of the atmosphere takes place. If less water is recycled back to the atmosphere, there will be less to condense and fall again as rainfall.

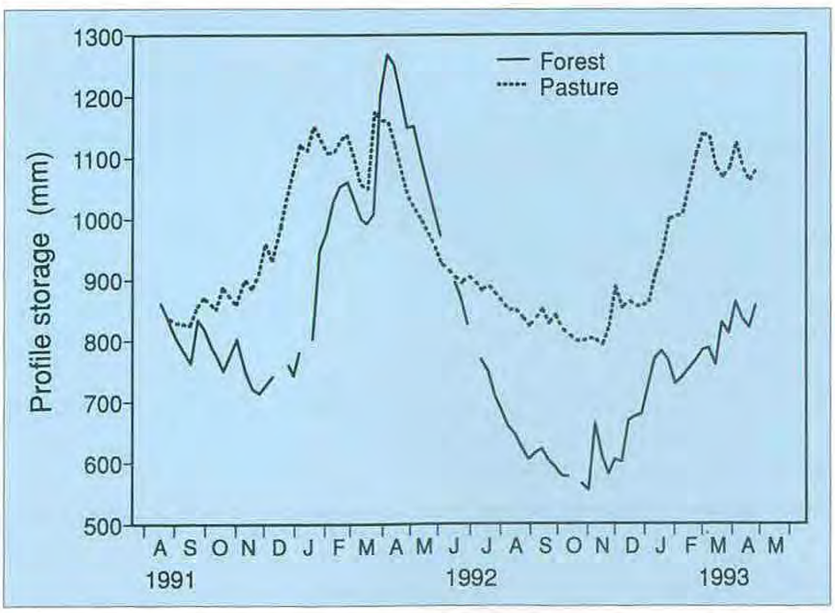


Figure 35 Profile water storage to a depth of 3.6 m for pasture (a) and forest (b) at the sites near Maraba, in the State of Para in eastern Brazil

Studies at the two newer sites in Amazonia set up in 1991 have shown similar results. Figure 35 shows the water storage of the soil profile to a depth of 3.6 m for pasture (a) and forest (b) at sites near Maraba in the State of Para in eastern Brazil.

Here the dry season is longer than at Manaus and the vegetation more dependent on the soil water reserve. The total seasonal soil water storage change was 370 mm in the pasture, but over 700 mm in the forest, the difference being mainly accounted for by differences in the rates of evapotranspiration. Of particular interest is the fact that while the profile at the pasture site wetted back up to the same extent in the 1992/93 wet season as in the previous wet season, the forest site profile storage was 400 mm lower, showing a carry-over of a very large soil water deficit into the 1993 dry season. Examination of the soil water profiles showed that little water had penetrated beyond a depth of 2.0 m. The forest is likely to suffer extreme stress and this will have important consequences on the energy budget and ecologically. Species at the limit of their ecological range may die as a result of the stress, changing the floristic composition of the forest. In addition, the forest will become vulnerable to fire.

River flow generation

Soil moisture processes are vital not only for agronomic purposes and for groundwater recharge but also play a crucial role in determining the amount and variability of river flows from a catchment. Similar rainstorms may generate very different river hydrographs, depending on the antecedent conditions. Work is being undertaken for MAFF and for the NRA to assess the contribution that continuous soil moisture measurements may make to improved predictions of peak flows.

Figure 36 shows the changing pattern of the river flow response to rainfall, together with the soil

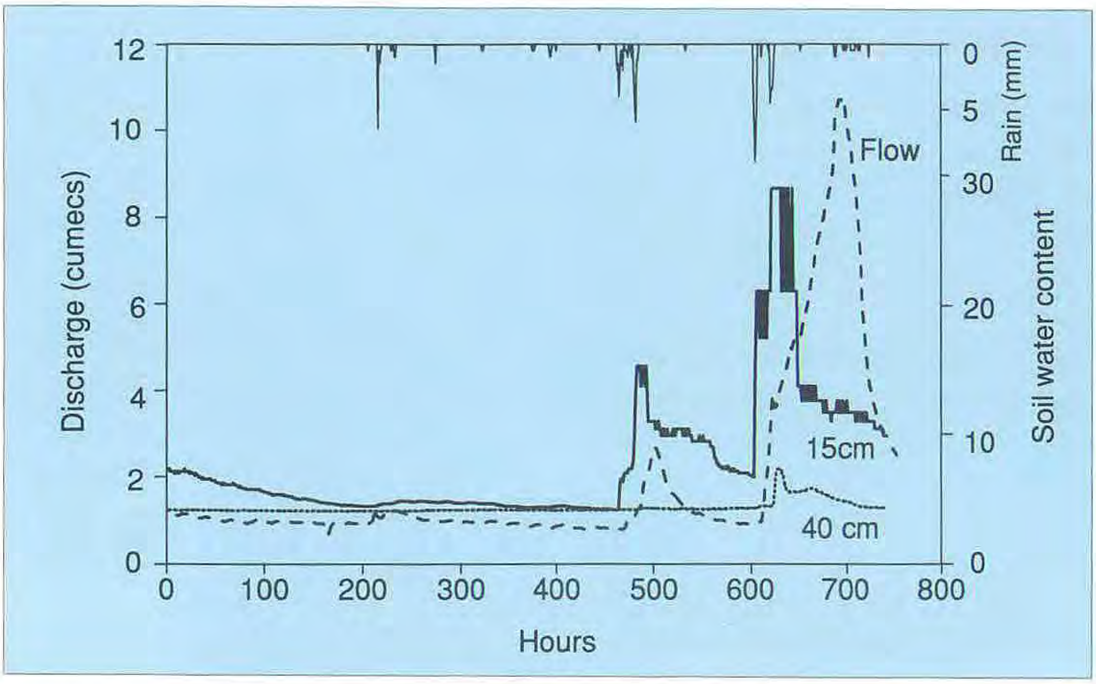


Figure 36 Variations in measured rainfall, streamflow and soil moisture during a series of storm events in spring 1993

water contents measured using capacitance probes at 15 cm and 40 cm depths in the soil profile. This demonstrates that for this catchment the near surface layers of the (clay) soil are the most important for storm flow. Such measurements offer the intriguing possibility of soil moisture data being not just a supplementary source of input information to refine rainfall-flood predictions, but also a cost-effective alternative to streamflow gauging in some situations where the siting of a gauging structure could not be justified.

Instrumentation

In the past, the main constraint on the ability to study the processes of soil water movement was the lack of instrumentation. This was recognised at IH in the mid-1960s and led to the development of the IH neutron probe, which in only slightly modified form, is arguably still the most important tool in soil water studies carried out at IH today.

A capacitance probe, undergoing development at IH, is gaining favour and generally complements the neutron probe. The capacitance probe measures the dielectric properties of the soil/air/water soil mix. One version is particularly suited to making measurements in the top 5 to 10 cm of the soil, where the neutron probe is least accurate. Other versions can be buried *in situ* and logged. This facility is extremely valuable in studies where processes may be changing rapidly. Installation of capacitance probe access tubes to more than 2.0 m depth or in stony soils has not proved possible because of the problems of obtaining a very tight fit for the tube, essential as the presence of air gaps between the soil and tube wall causes inaccurate readings. In these situations, the role of the neutron probe is unchallenged.

Time Domain Reflectometry (TDR) is another promising method being examined by IH researchers, also based on the measurement of the dielectric properties of the soil, although through a different principle than the capacitance probe. Further developments and improved understanding of the TDR and capacitance methods appear to be required before they can supplant the neutron probe as the mainstay of field soil water content measurements. However the choice of the best equipment will depend on the environment, and on the monitoring requirements. The humble mercury manometer tensiometer is still the method of choice for soil water potential measurements, but these are now augmented by IH-designed purgeable pressure transducer tensiometers (PTTs) which can be logged. Gypsum resistance blocks are used to measure soil water potentials beyond the range in which tensiometers can operate.

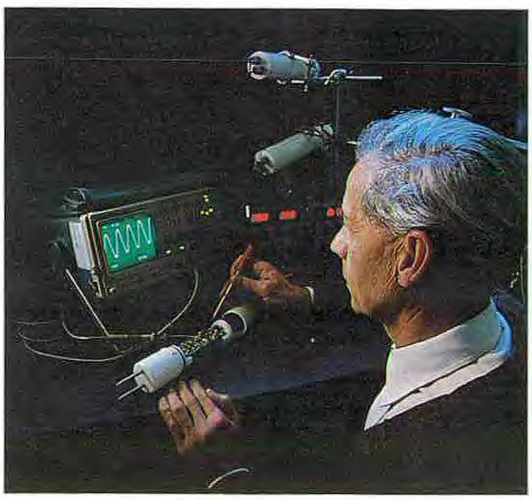
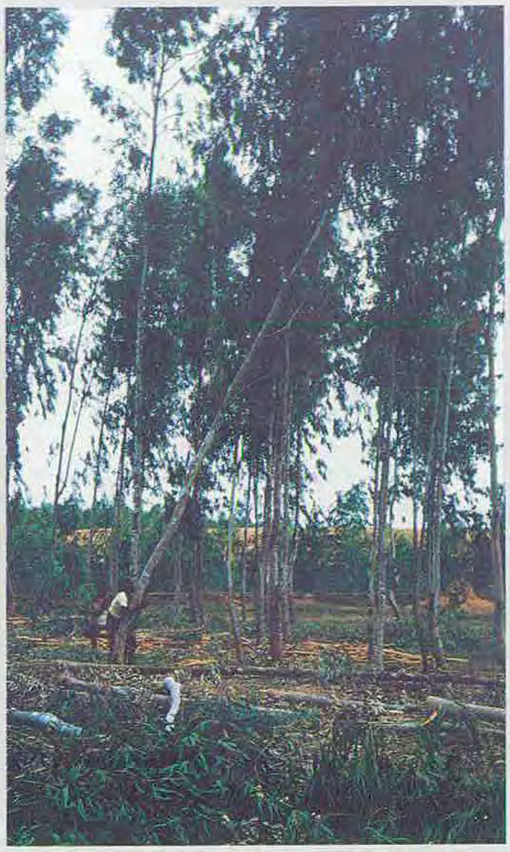


Figure 37 The IH capacitance probe on test

The Eucalyptus story

Within the tropics and sub-tropics approximately half the plantation forestry is of *Eucalyptus* species. Their high growth rates and their ability to grow within a wide range of site conditions make them attractive species for both commercial and social forestry applications. The large-scale planting of these exotic species has caused concern to local people in many tropical countries, not least in southern India, where the plantations are thought to have deleterious socioeconomic effects at the village level, providing little employment, poor firewood and no fodder for animals. There are also concerns about possible adverse envir-onmental impacts, particularly depletion of nutrients, high water use and enhanced soil erosion.

In response to these concerns, a programme of field studies was initiated in the state of Karnataka, southern India, to quantify the impacts. The collaborating organisations were the Karnataka Forest Department, Mysore Paper Mills and the University of Agricultural Science, Bangalore, in India, and IH and the Oxford Forestry Institute in the UK. The studies were funded by the Overseas Development Administration.



Scientists from IH carried out hydrological studies at four main sites in Karnataka. Three of them were in the low rainfall zone (800 mm per annum) at the Devabal and Puradal experimental plantations near Shimoga and at Hosakote near Bangalore. The soils are of different depths, approximately 3 m at Devabal and Puradal and greater than 8 m at the Hosakote site. The fourth site at Behalli is in the high rainfall zone (2000 mm per annum) on deep soils (greater than 8 m).

Measurements were made of the meteorology, plant physiology, soil water status, rainfall interception and direct water uptake of individual trees using tracing methods. The growth rates of the trees were also measured. Water use, as ascertained by the different experimental methods, was generally in agreement at all sites.

The deuterium tracing method for measuring transpiration revealed a new, and surprisingly 'tight', relationship between individual tree transpiration and the cross-sectional area of the trunk. A model for growth and water use of *Eucalyptus* plantation in water-limited conditions was developed using this relationship and also the assumption that volume growth is linearly related to the volume of water transpired.

The main findings of this work are:

- In the dry zone, the water use of young *Eucalyptus* plantation on medium depth soil (3 m deep) was no greater than that of the indigenous dry deciduous forest.
- At these sites the annual water use of *Eucalyptus* and indigenous forest was equal to the annual rainfall (within the experimental measurement uncertainty of about 10%).
- At all sites, the water use of forest was higher than that of agricultural crops (about twice).
- At the dry zone deep soils (>8 m) site there are indications that the water use, over the three (dry) years of measurement was greater than the rainfall. Model estimates of

evaporation were 3400 mm compared with 2100 mm rainfall for the three-year period.

- At none of the sites was there any evidence of root abstraction from the water table. (Where this has happened in Australia there are reports of annual *Eucalyptus* water use of 3600 mm in areas where the rainfall is only 800 mm.)

More recently, the research has widened in scope to look at the erosion impacts of these forest, the water use of *Acacia* and *Pinus* species in the wet zone of Karnataka, and also towards improving the water use efficiency of plantations.

Erosion impacts

Forests can influence soil erosion by altering the erosive potential of rainfall. Contrary to popular belief, forest canopies do not necessarily 'protect' the soil from raindrop impacts. For storms with small raindrop sizes, such as are usually associated with storms of low intensity, canopies tend to amalgamate drops until a large drop is formed, which is then released from the leaf. If the vegetation is sufficiently tall, this large drop may reach such a velocity before it reaches the ground that it has a higher potential for detaching soil particles on impact than do natural rain drops. Conversely, for storms with the largest drop sizes, often associated with the convective storms common in the tropics, vegetation canopies may break up the large drops and reduce both the mean drop size and the mean kinetic energy of the incident rain.

Studies carried out at the Puradal and Hosakote sites have shown that not only are there large differences in the drop size spectra beneath different tree species but that each species — irrespective of the drop size of the incident rain — has a spectrum characteristic of that species.

The erosivity of natural rainfall is related to its intensity. As rainfall intensity increases, the size distribution of raindrops generally increases also, which provides a means of relating the erosivity of

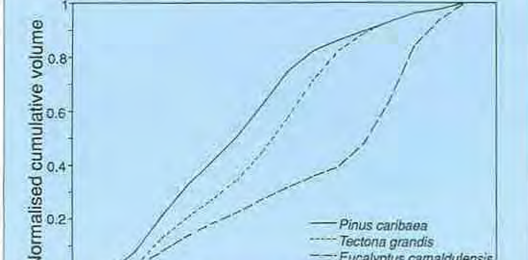


Figure 38 *The characteristic net rainfall spectra for Pinus caribaea, Eucalyptus camaldulensis and Tectona grandis*

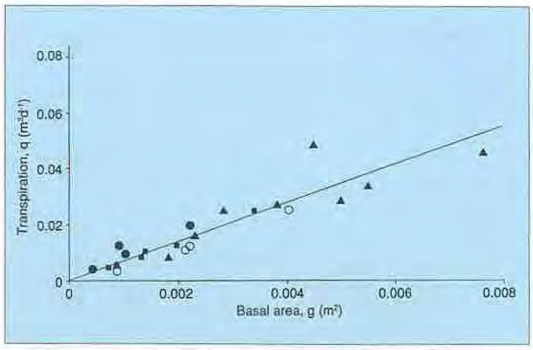


Figure 39 *Measured transpiration as a function of tree basal area (g) for all sites for measurements made under (relatively) non soil-moisture stressed conditions*

the characteristic spectra to the erosivity of rainfall of different intensities. The presence of an understorey of vegetation will also moderate the erosivity of the raindrop impact, so that plantations with a dense understorey are less subject to erosion than those without.

Water use efficiency

The recognition that forests generally evaporate more water than agricultural crops and that water is a valuable resource provided an impetus for trying to improve the water use efficiency of plantation forests.

Both growth rates and water use efficiency of the eucalypt plantations in the dry zone in India are low by world standards. To some extent, this is due to climatic factors which are not amenable to manipulation. (High vapour pressure deficits, through increasing atmospheric demand, are known to decrease water use efficiency and high temperatures, leading to high rates of maintenance respiration, also have a depressing effect.) Nevertheless, it is believed that there is still great potential for improving stand water use efficiency through, for example, species selection, through the removal of nutrient and water stress, and through improved silviculture practices such as optimal spacing and weeding.

These aspects are presently being investigated within a Controlled Environment Facility where three tree species *Eucalyptus camaldulensis*, *Eucalyptus grandis* and an indigenous species *Dalbergia sissoo* are being subjected to different soil water and nutrient stresses. Results from the experiment so far indicate that growth rates can be increased by a factor of five between the control plots and those which receive both water and fertilizer treatments.

After this first year, when soil water reserves are largely used up on the control plots and greater soil water stresses are expected, even larger proportional differences in growth rate are anticipated, perhaps by as much as ten times.

In later years, when the utilisation of soil water reserves is small in relation to the amounts of water

Figure 40 The Controlled Environment Facility, August 1992

applied, estimates of maximal water use can be equated to the water application rates (plus any rainfall that may occur) and lower limits for the water use efficiency can then be obtained. Using this approach for the volume growth, values recorded for the first year did not provide any evidence for increasing water use efficiency with increasing water applications. However, it did indicate that water use efficiency increases with increasing fertilizer applications (see Figure 41).

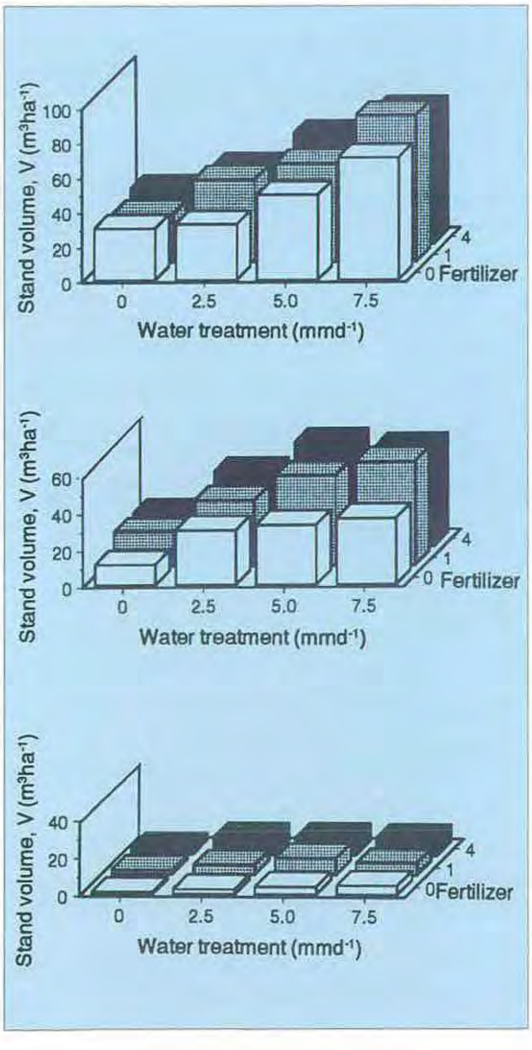


Figure 41 Stand volume recorded on 29 September 1993 for Eucalyptus camaldulensis, Eucalyptus grandis and Dalbergia sissoo (top to bottom) for a range of water treatment and fertilizer application on the Controlled Environment Facility at Hosakote, India

Water resource implications

The hydrological studies carried out in southern India on plantations of exotic tree species, indigenous forest, and agricultural crops show a complex pattern of hydrological impacts resulting from afforestation using exotic species, some of which are adverse and some of which are beneficial.

The net-rainfall dropsize spectra associated with exotic species such as *Pinus caribaea* or *Eucalyptus camaldulensis* make them preferable, from a soil conservation perspective, to *Tectona grandis* which has a characteristic net rainfall of potentially greater erosivity.

At the Devabal and Puradal sites where the water use of eucalypt plantation has been compared with that from indigenous forest there is no evidence that *Eucalyptus* species use more water than the indigenous dry deciduous forest. They do however use more water than a typical annual crop: about twice as much as ragi, a finger millet.

The Hosakote findings, which showed water use greater than the rainfall, have potentially serious water resource implications. Further studies are being planned to confirm these results and also to determine the source of the 'extra' water. One hypothesis invokes soil water 'mining'. If, from the day of planting, roots penetrate successively deeper layers in the soil, at a rate of about one metre per year, the water 'mined' from the successively deeper soil layers would be sufficient to account for most of this extra water.

An alternative or additional hypothesis is that the trees are drawing on water stored in the soil from years with higher than average rainfall. The measurement period, from 1987-1990, had much lower than average rainfall. The first hypothesis implies that unless roots can continue to penetrate deeper each year until they reach the water table (at 30 m) present rates of growth will not be sustainable in the longer term; the second hypothesis would, of course, imply sustainable growth rates.

If the former hypothesis is shown to be true then one sensible strategy would be to rotate *Eucalyptus* plantation with agricultural crops. If a rotation of ten years for the forest were to be followed by five years under an annual crop, the soil water reserves built up during the agricultural phase would replace those removed during the period under forestry. There is also evidence from studies in other arid zones of the world that deep rooted trees have the ability to bring nutrients from

Figure 42 *Harvesting eucalypts in Karnataka, India*

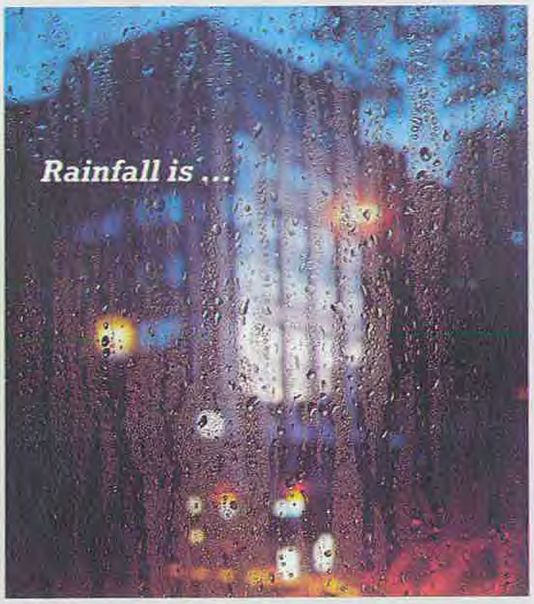
deep soil layers up to the surface. If this is true of eucalypts in India, there would be dual benefits from the rotation: trees replacing soil nutrients the agricultural crops remove whilst crops recharge soil water that the trees have removed.

The forest water-use results indicate that recharge to the groundwater under large areas of either plantation or indigenous forest in the dry zone of India is likely to be small and will not, on average, be more than 10% of the rainfall. However, if plantation forests were grown as a "patchwork", interspersed with annual agricultural crops, many of the adverse effects on the water table would be alleviated since up to half the annual rainfall should be available for recharge under the agricultural crops.

In theory, a patchwork design with irrigated areas of forestry could be optimised such that it would be possible to grow the same volume of timber, using irrigation, on one fifth to one tenth of the land area leaving the rest for rainfed agriculture. There may also be economic advantages to this type of scheme: if the plantations are close to the pulp mills, transport costs would be minimised, which could halve total production costs.

The feasibility of such schemes is, of course, critically dependent on economic issues such as the value of water consumed in the production of timber in relation to the value of the timber, and the social impacts that these schemes might entail. These social and economic impacts are currently under consideration elsewhere.

Rainfall affects everyone



In our temperate climate, rainfall is the dominant input to the land phase of the hydrological cycle. While temperature and wind interfere from time to time, rainfall is the meteorological variable that demands our attention most often. Will it rain today? Will rainfall this winter replenish reservoirs and aquifers? Will there be a flood? The complexity of rainfall, its variability and intermittency in time and space, make it difficult to monitor, challenging to forecast, and problematic to put bounds on.

Rainfall has long been the subject of experimental measurement and statistical analysis. However, atmospheric processes are still not sufficiently well understood to meet all of society's interests in rainfall prediction. Most requirements fall into one of two categories: the estimation of long-term *extremes* (e.g. for the design of structures to control or withstand flooding) and the estimation of *present and future* rainfall intensity (e.g. for public information, irrigation management, or real-time forecasting of floods).

Data sources

The UK has a good network of raingauges which provide information about rainfall depths at individual points in space for a range of durations. The last decade has seen the development of the UK weather radar network, which gives a detailed description of rainfall in both time and space, thus offering a unique opportunity for basic research into the science of the precipitation process and its link with runoff response. This year saw the start of the Hydrological Radar Experiment (HYREX) Special Topic, described in detail in the section on *Flood forecasting and weather radar*.

How many storms make an event?

It is tempting to envisage a one-to-one relationship between storms and flood events. Figure 43 comes from a study of flood response times on small catchments, and shows *concurrent* water level variations for six catchments of varied land use and underlying geology, near Luton (Figure 44). It is clear that the number of runoff events generated over the four-day period is strongly influenced by the response characteristics of the particular catchment. Thus it is *appreciable rainfall over a period of time relevant to the particular catchment* that determines flood formation: this may represent an extreme storm, several storms in quick succession, or a less extreme rainfall episode occurring when the catchment is unusually ripe for flood production. Catchment 4 shows a "partial contributing area" effect, with rapid runoff from an urban area close to the basin outlet, but — on this occasion — no response from the highly permeable chalk areas.

It all depends ...

A group specialising in studies of Flood and Storm Hazard has broken new ground in the assessment and modelling of *dependence* in rainfall extremes. Inter-site dependence arises because extreme rainfall events are often spatially extensive and are gauged at more than one site. Similarly, temporal dependence arises because many rainfall events presenting an extreme accumulation over one duration (e.g. six hours) appear also in longer-duration extremes (e.g. one day) at the same site.

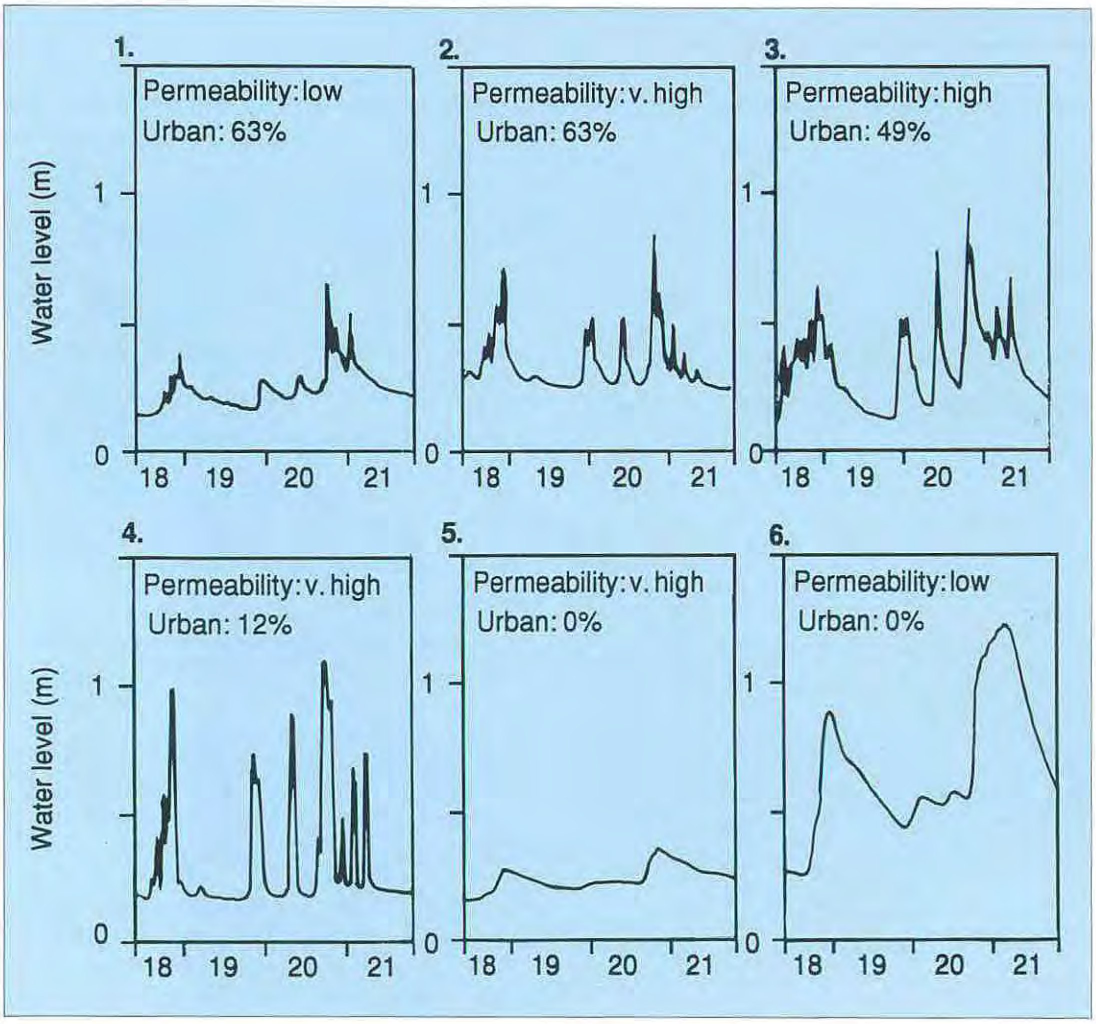


Figure 43 *Water level response of six small catchments, 18-21 December 1989*

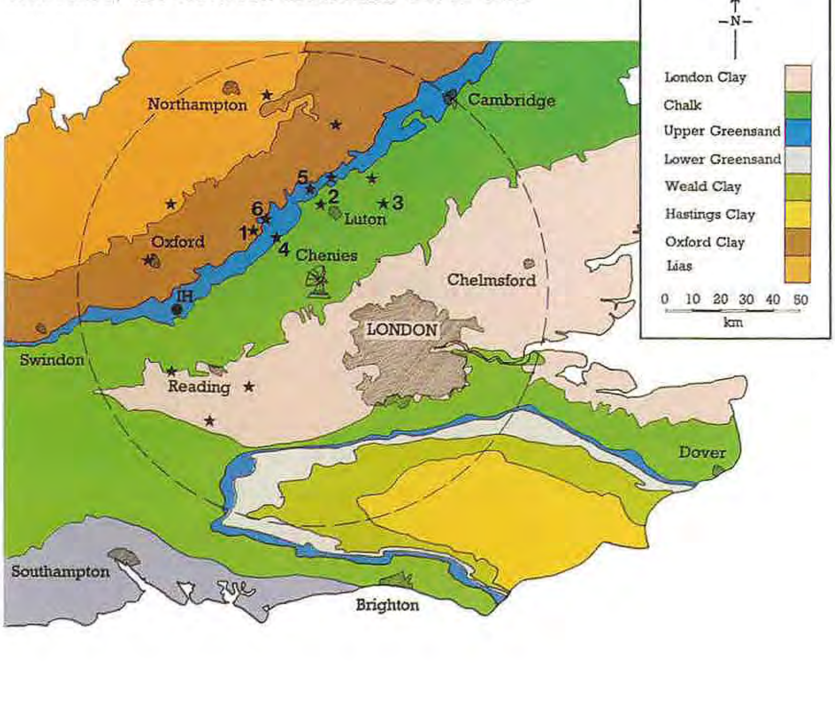
Indexing dependence

Figure 45 illustrates an empirical measure of dependence which is proving particularly useful. The lowest curve represents the typical rainfall frequency relationship in a district, obtained by *pooling* long-term annual maximum 1-day rainfall data from several sites.

Data are standardized before pooling to take account of systematic differences between sites, such as those which are due to orographic effects. Derivation of the pooled frequency curve assumes that, in other respects, the extreme values observed at each site are identically distributed. In some applications, the hypothesis is made that the standardized annual maxima follow a Generalised Extreme Value (GEV) distribution. The distribution is fitted to the data using a regional version of the method of probability-weighted moments. Related statistics, called *L-moment ratios*, are useful in confirming that a proposed pooling makes sense and that the choice of distribution is reasonable.

The middle curve in Figure 45 represents the frequency relationship for the *network maximum* rainfall. This derives from the annual maximum series of the largest standardized rainfall observed by the network of N sites. In the absence of dependence, a theoretical result shows this frequency curve to lie a distance ln N to the left of that of the parent GEV distribution. In practice, because of the partial dependence in rainfall extremes, the network maximum curve falls

Figure 44 *Location of water level recorders in small catchment response times project (funded by MAFF)*



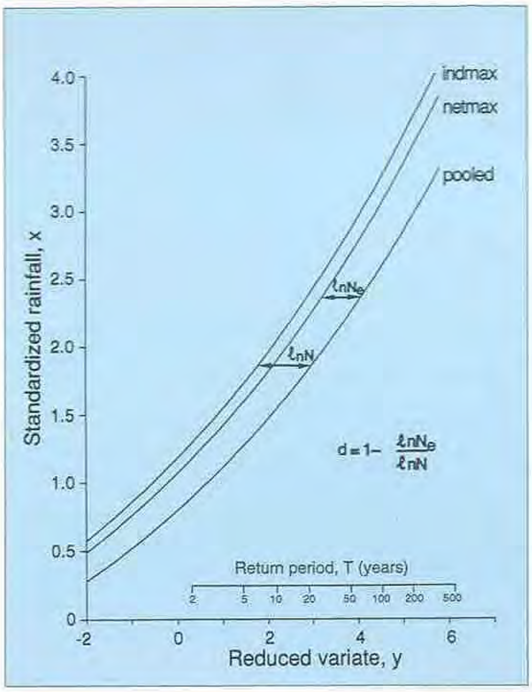


Figure 45 *Indexing the degree of dependence, d, in rainfall extremes*

between the wholly dependent (netmax = pooled) and the wholly independent (netmax = indmax) cases. Its relative position therefore indexes the degree of dependence in the rainfall extremes at the N sites.

Applications

Initially, the Institute developed dependence models to solve the rather esoteric problem of assessing the collective risk of experiencing an extreme rainfall at one or more of a network of sites. However, the research has matured to further applications, including the solution of an old and important problem: how do you estimate the 1000 or 10,000-year rainfall extreme (required for reservoir safety design) from gauged record lengths of only 10 to 100 years?

Thoughts of long-term climatic change are avoided by defining the T-year extreme as the event that has an annual exceedance probability of 1/T. *[Imagine shaking four dice annually, on your birthday. Scoring 24 would have an annual exceedance probability of 1/1296. This highest score could happen next year; on the other hand, you would have to shake for 898 years to have an even chance of the experience!]* The route to achieving consistent estimates of very rare events is to pool data from many sites. This has been extended in recent research to consider pooling rainfall extremes data both from a group of sites and for a range of durations.

Alternatives to pooling are far less attractive. Undue extrapolation of frequency curves fitted to data from individual sites or durations inevitably leads to inconsistencies in estimates, e.g. inferred 2-day maxima falling short of inferred 1-day maxima! Scope for contradiction is reduced by choosing a less flexible distribution, such as the 2-parameter Gumbel distribution. However, analysis of long-term records indicates that the Gumbel distribution is not sufficiently skewed to be representative of short-duration rainfall extremes in many regions of the UK.

Dependence in rainfall extremes is detrimental in the sense that pooled information provides many fewer effective site-duration-years of record than in the independent case. However, there is also good news in dependence: it is evidence that extremes within a district show association. Indeed, the *absence* of dependence between extremes from neighbouring sites and adjacent durations would largely undermine the hypothesis that their distributions are sufficiently similar to permit pooling.

Too many droughts?

Assessing the rarity of droughts may at first sight seem a rather different problem. Supply companies are reluctant to impose restrictions on water use and, before doing so, must convince customers and regulators that the drought is exceptional. In such circumstances it is usual to turn to long-term rainfall data as an independent arbiter, to demonstrate that the problem arises from nature rather than mismanagement.

Tables provided by the Met. Office allow return period assessments to be made for accumulations over a certain duration from a fixed starting date (e.g. five months beginning in March). Despite caveats, these assessments are often misinterpreted. Thus a drought is characterized by the severest extreme thrown up in an analysis of monthly data - i.e. the rainfall accumulation at a particular site, beginning in a particular month, that yields the highest return period. This is done without regard for the fact that the resource is not uniquely sensitive to this choice of duration and starting month.

The approach to be taken in new research is to use a dependence model to estimate the annual *collective* risk of experiencing a T-year rainfall minimum for one or more of the combinations of durations and starting months that are relevant to the security of the water resource.

A matter of fractal?

A fractal is a structure that exhibits self-similarity over a range of scales. Two areas in which fractal methods show particular promise are in studying stream networks and rainfall patterns. But can fractals do more than provide a neat summary of structure?

"Disaggregation of rainfall" has become an important quest for hydrologists. The problem is important if modelling the land surface/atmosphere

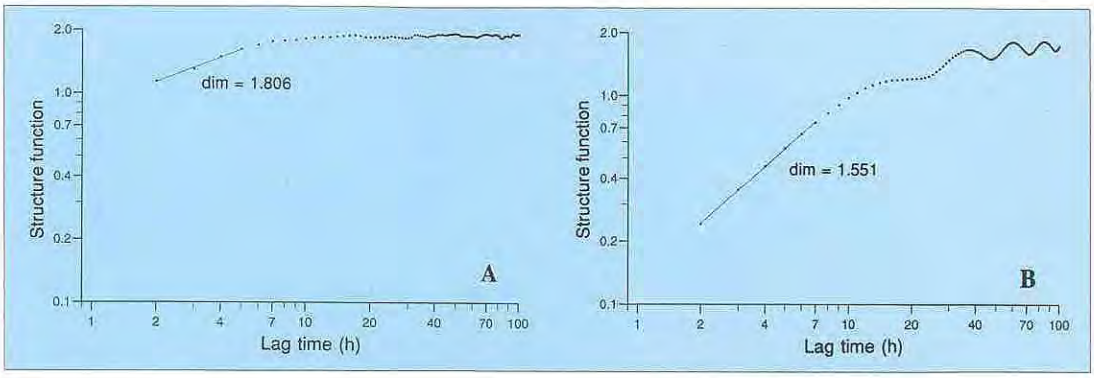


Figure 46 *Structure function: (a) hourly wind data, Eskdalemuir; (b) hourly rainfall, Eskdalemuir*

interaction within Global Climate Models is to be advanced. Given an average value of rainfall in time or space, is it possible to construct greater detail in time or space? The answer would appear to be "yes", if it suffices that the generated detail is realistic rather than real. However, there is uncertainty as to how it will be possible to constrain generated rainfall fields (i.e. spatially gridded values) so that they are consistent from one time interval to the next.

A research project at the Institute has compared the temporal structure of environmental variables — such as rainfall, wind and temperature — using long records of high-resolution data. The study has assessed the adjustment factors necessary to correct extreme values for *discretization* errors. An example of a discretization effect is where the interest is in 24-hour extremes (from *any* starting time) but an analysis must be content with daily data (from a *fixed* starting time, e.g. 0900 h).

The project has found that the correction factor of 1.11, used in the UK to adjust for discretization effects in maximum rainfall estimation, is too low; the factor applied in other countries (typically 1.13 or 1.14) also appears low. Rainfall is an exceptionally erratic and intermittent variable. Discretization corrections required for other variables such as wind speed and air temperature have been found to be more modest.

It is reasonable to expect the discretization effect to be linked to the relative "roughness" of the environmental time-series, to which fractal dimension provides a natural index. The fractal dimension is conveniently estimated from the slope of the temporal variogram or *structure function*. Self-similarity is indicated by a linear structure function at small lag times, and is seen from Figure 46 to be more readily discernible for wind speed than for rainfall.

The wind speed data (Figure 46a) show self-similarity over the range two to seven hours. Data with a higher temporal resolution would be required to demonstrate the extent to which "scaling" behaviour extends below two hours. Linearity within the structure function is less convincing for rainfall (Figure 46b). Analysis of many rainfall series of different time resolution has lent support to the argument that rainfall is multifractal, i.e. exhibiting self-similarity but in a less simple fashion.

It has been found that fractal dimension provides a broad guide to the extent to which corrections for discretization are needed in the analysis of extremes. The correction factor in Figure 47 is that required when estimating 24-hour extremes from daily data. The environmental variables shown are aggregations (for rainfall) and means (for wind speed and air temperature), although the project has also considered some *sampled* series, i.e. regular instantaneous measurements such as hourly sea level observations.

Assessment of discretization errors for *irregularly* sampled series has yet to be resolved. This may be important in enforcing compliance with conditions for effluent discharges to rivers.

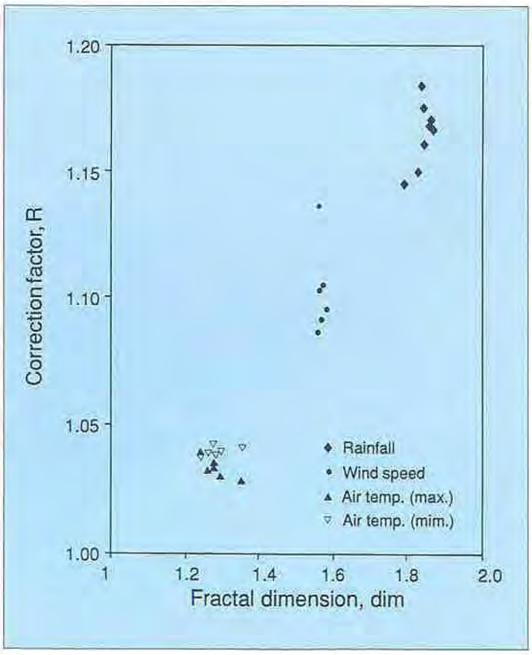


Figure 47 *Fractal dimension as a guide to correcting for discretization: replicate data series, Eskdalemuir*

Flood forecasting and weather radar

Deaths from flooding worldwide exceeded 100 thousand over the quarter century ending in 1990 but as many as three quarters of a billion lives were distressed or disrupted in some other way. These statistics reveal that of all natural disasters flooding affects the greatest number of people on the planet Earth. Control of flooding by structural measures, such as the building of flood alleviation dams and embankments, will never achieve absolute protection from flood risk. The building of embankments along the Mississippi has demonstrated this fact in a dramatic manner this year by showing how embankments reduce the frequency of flooding but increase the damage when failure eventually occurs. In many instances more cost-effective alleviation of flooding can be achieved through flood warning or a combination of flood protection and warning. The Institute is at the forefront of research and development of flood forecasting systems and is responsible for the implementation of a number of schemes in operation in the UK and overseas. In 1992 it was awarded a British Computer Society medal in recognition of the excellence of the River Flow Forecasting System (RFFS) developed with Logica Ltd and the National Rivers Authority for flood warning and day-to-day management of Yorkshire's rivers

The River Flow Forecasting System

An initial alert of possible flooding can be based on actual measurements of heavy rainfall from a raingauge network and from weather radars. It can also be based on forecasts of rainfall derived from weather radars, from synoptic analyses and from mesoscale models. More precise information, for use as a basis of flood warning to specific localities, requires hydrological and hydrodynamic models capable of forecasting the rising water level at many locations within a single river basin, or across a whole region with several river networks. The complexity of the forecasting and flood warning dissemination task demands that automated systems are developed to coordinate and provide simple support to assist decision-making under conditions of uncertainty.

Figure 48 *The London Flood Warning Centre (Photo: National Rivers Authority Thames Region)*

The RFFS provides a generic River Flow Forecasting System which can coordinate the task of flood forecast construction for both simple and complex river networks. The first implementation of the RFFS provided forecasts at some 150 locations within the 13,500 km^2 region of Yorkshire, England. This system operated on a trial basis from February 1992 and by April 1993 the experience gained was sufficient to allow forecasts upstream of York to be used for routine flood warning.

The versatility of the RFFS was demonstrated through its use as the basis of the White Cart Water Flood Forecasting System: this small system provides flood warning to the southern part of Glasgow, Scotland, and involves six forecast points supported by telemetry of six river gauging and four raingauge sites. This application demonstrates how the kernel software is largely machine independent (transferable from a VAX to a Data General computer) and suitable for both large, regional warning schemes and small catchment situations. Most recently the system was transported to a UNIX workstation to provide forecasts at sites in a 70 km^2 basin in the New Territories, Hong Kong. A further UNIX application is proposed for the 27,000 km^2 Anglian Region of England where nearly 600 locations have been identified as needing forecasts, the majority for flood warning but also for managing water transfers and licensing at lower flows. The aim in this case is to provide a unified Windows-based environment for water management during floods, droughts and pollution incidents. Extension to water quality is clearly possible given the generic nature of the system's central information control algorithm and is the subject of an ongoing study.

Spatial variability and weather radar

Progress in real-time flow forecasting has been constrained by the use of point estimates of rainfall obtained from an often sparse network of rain-gauges. Weather radar's ability to estimate rainfall continuously over space now provides an exciting prospect for improvement of forecast accuracy. The national radar network, operated by the UK Meteorological Office, has serviced well the primary function of the daily weather report and forecast: the visual images of the spatial extent and propagation of storms are now a familiar feature of reporting on television. However, the need for quantitative rainfall estimates for input to flood forecasting models has not been so well met.

This led the Institute to develop local methods for radar calibration and forecasting, particularly in collaboration with the National Rivers Authority's London Flood Warning Centre located at Waltham Cross. Here, the potential advantages of a local radar calibration procedure were apparent in that data from some 30 gauges were available via telemetry in addition to the five gauges used for calibration at the radar site. The calibration procedure developed for an area 60 km square containing up to 30 gauges provides, on average, an improvement in accuracy of 22 per cent relative to the uncalibrated radar. The calibration system has operated at the London Flood Warning Centre since March 1989.

The success of this calibration study was followed by a radar rainfall forecasting project. This developed a forecasting procedure which infers the speed and direction of movement from two time-displaced radar images and these are used, with the current image, as the basis of forecasting. The algorithm outperforms not only a persistence (no-change) forecast but also the national FRONTIERS rainfall forecasts. The latter complements the local method in providing forecasts for longer lead times when the local method, based on a single radar, suffers from exhaustion of the field being advected forward. This system has operated at the London Flood Warning Centre since November 1991.

The above developments created two distinct, but uncoupled, tools whereby weather radar can be used to better support flood warning. The forecasting study also produced algorithms to preprocess the radar data to suppress transient clutter and to remove more permanent anomalies, due to blockages in the radar beam. A clear need existed to integrate these preprocessing, calibration and forecasting procedures within a single integrated HYdrological RADar system and as a result the IH HYRAD system was conceived. The kernel to the system comprises the above procedures together with a post-processor to derive catchment average

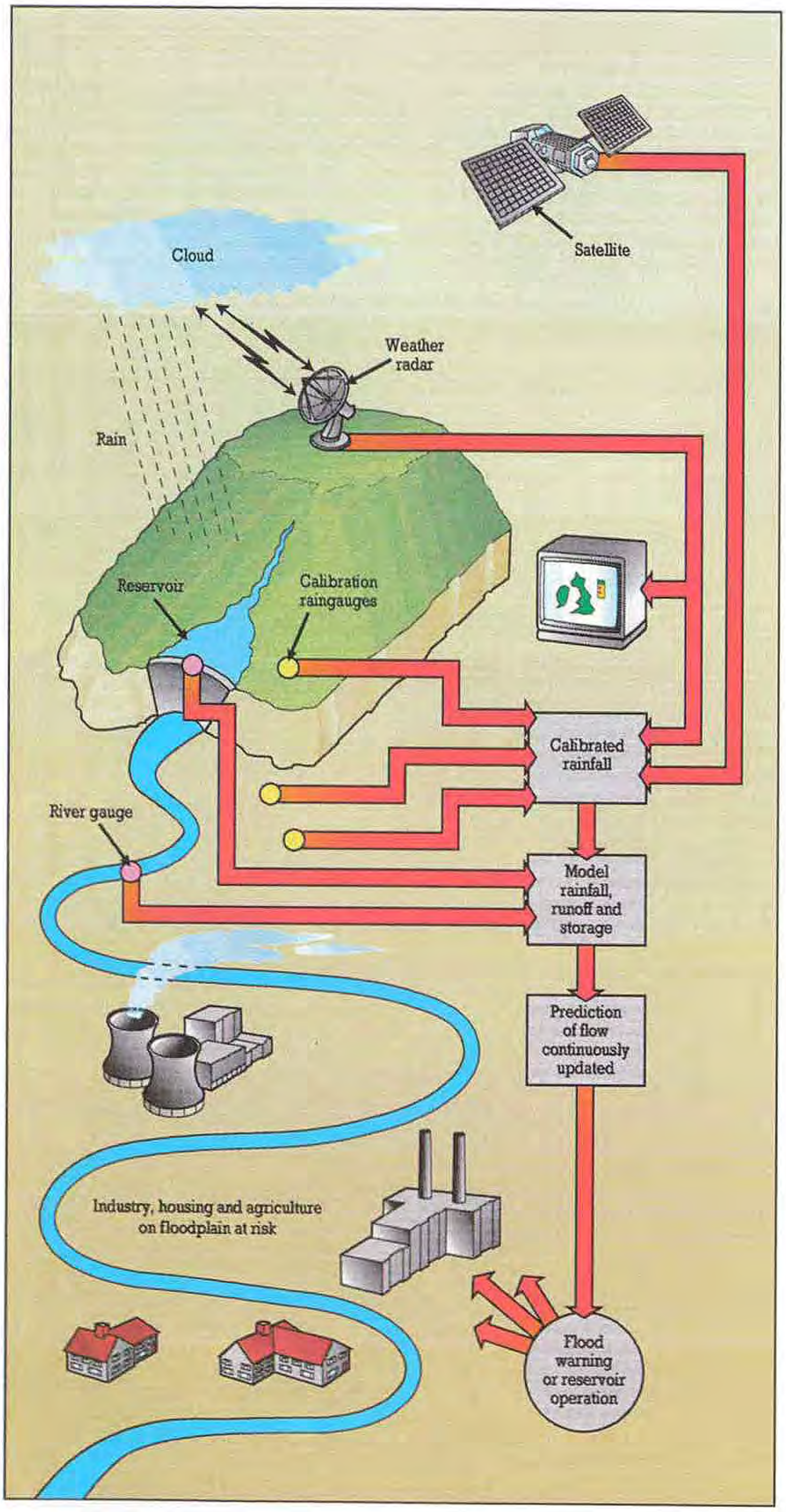


Figure 49 *River flood forecasting*

rainfall time series data (utilising digitised catchment boundary data) and an interface to the River Flow Forecasting System.

Network Design Study

The value of weather radar to provide a continuous estimate of the rainfall field over space is well appreciated in qualitative terms. However, when quantitative rainfall estimates are required, for example for flood forecasting, the more accurate point estimates of rainfall from a network of recording raingauges can also be of great value. Clearly a combination of the spatial detail provided by radar and the point accuracy offered by raingauges provides a means of deriving better quantitative estimates of rainfall over a region. A recent investigation explored how rainfall estimation accuracy is affected by raingauge networks of differing density, thereby obtaining guidance on the optimal number of raingauges to combine with a weather radar to achieve a given level of accuracy.

A total of 13 events between June 1990 and April 1991 were selected for study, for which measurements were available from a common network of 44 gauges. So-called 'design networks' were created from this base network containing progressively fewer gauges. Gauges were selected for deletion to create a network at the next density level based on first identifying the pair of gauges with the smallest inter-gauge distance and deleting the one which is nearest to any of the others. The result is a set of 43 design networks containing from 44 to 2 gauges and varying in terms of mean distance between gauges from 6.64 to 78.6 km.

Figure 50 shows the results obtained when the root mean square estimate (rmse) criterion is pooled across the 13 events and plotted against the number of gauges in the design network. A similar multiquadratic surface fitting method was used to infer the rainfall field from the gauge network alone, this time fitting the surface directly to the point measurements of rainfall. The rmse resulting from this 'raingauge only' estimate as a function of number of gauges in each design network is shown on the same figure. Finally, the rmse, calculated using the 'radar-only' rainfall estimate and without using raingauges for calibration, is also displayed. The figure suggests that as many as 30 gauges are required before the accuracy of the uncalibrated radar can be achieved, equivalent to a spacing of 9.2 km between raingauges. The accuracy of the calibrated radar continues to increase with increasing numbers of gauges but at a progressively diminishing rate. This information might be used to support a choice of raingauge network to be used in combination with a weather radar.

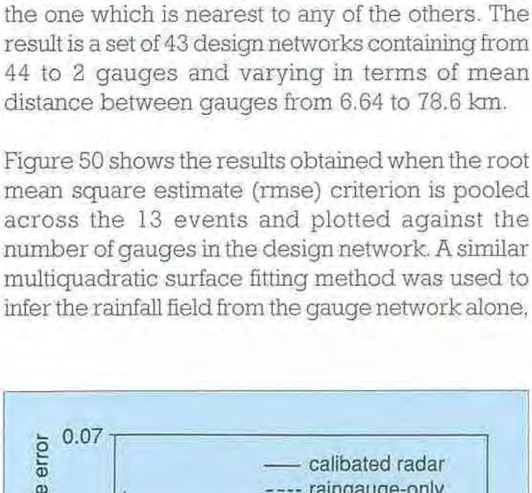


Figure 50 *The effect of the number of gauges on rainfall estimation accuracy: the results were averaged over 13 events*

A more detailed analysis on an event by event basis reveals that there is considerable variation about the average results arrived at by pooling across the 13 events. As a result, any recommendation concerning an optimal number of calibrating raingauges must be highly circumspect. Transient factors influencing the optimal number include the effect of bright-band due to melting precipitation and the problem of beam-infill (where the higher radar beam elevation is used in place of the lowest when this is blocked by local obstructions) associated with shallow rainfall-forming clouds. In such conditions the value of radar is least and the complementary role of raingauges greatest.

Radar rainfall forecast evaluation study

Whilst an assessment of the IH local radar and Frontiers national rainfall forecasting systems had been undertaken with reference to rainfall accuracy, this had not extended to an assessment in a flood forecasting context. A two-year study for the NRA was completed in 1993 which assessed the usefulness of rainfall forecasts in flood forecasting models by simulating as nearly as possible the operational situation that exists in UK flood warning centres.

The evaluation considered three rainfall-runoff models of varying complexity applied to 30 storm events over nine catchments in the Thames basin with varied hydrological characteristics. Rainfall input to the models derived either from raingauges or weather radar data in raw form, in raingauge calibrated form and in the form of forecasts derived from the national Frontiers and Local Radar Rainfall Forecasting systems. Whilst the Local Radar Rainfall forecasting scheme applied to locally calibrated data was shown to provide the best performance overall, the improvement over a single Markov chain method used as a baseline was not significant, except for the smaller catchments. However, the benefits of radar are likely to be greater for catchments less well endowed with raingauges than was the Thames basin.

Further questions addressed were the choice of rainfall-runoff model updating technique to use and the sensitivity to radar data resolution and time interval. The similarity of the three rainfall-runoff models in their construction from a rather small set of model components was recognised. There is a trade-off between model simplicity and ease of application and model complexity giving greater flexibility at the expense of parameter identifiability.

Ideally, model complexity should be matched to hydrological model response through the use of tailored models. The PDM (Probability Distributed Moisture model) provided a compromise, in giving a reasonable level of flexibility whilst offering the most resilient forecasts. The choice of updating method was not clear-cut but generally state-correction was better where non-linear soil moisture effects dominate catchment response whilst error-prediction had advantages where linear, time of translation effects were important. Lower radar resolution (3 bit, 5 km) had an effect on radar recalibration at higher values but, given their limited severity, the events considered in the study failed to show much sensitivity in the model forecasts. Use of an hourly time step, instead of 15 min, for flow computation caused a significant drop in performance, especially at lower lead times, associated with the less frequent forecast updating.

HYREX: Hydrological Radar Experiment

Over the last decade the UK has led the world in the operational deployment of ground-based weather radars and these are now routinely used to support forecasts of weather and river flooding. However, enormous opportunities still exist for basic and fundamental scientific research using weather radar. A major constraint on the improved understanding and mathematical description of water movement in both the land and atmospheric phases of the hydrological cycle has been the difficulty of making spatial measurements of precipitation flux. Weather radar now provides the means to measure precipitation, in different phases, in both two and three dimensions, providing an important opportunity to advance our science. It is against this background and need for more basic research that the Natural Environment Research Council has formulated a Special Topic Programme called HYREX to address such issues. Additional support in the form of infrastructure has been provided by the NRA, MAFF, the Met. Office and the water utilities. Six research awards have been granted which will fund the use of radar to investigate rainfall measurement using new types of radar, to formulate both stochastic and physics-based rainfall models at the hydrological scale and to investigate catchment flow models and processes supported by improved information on rainfall input.

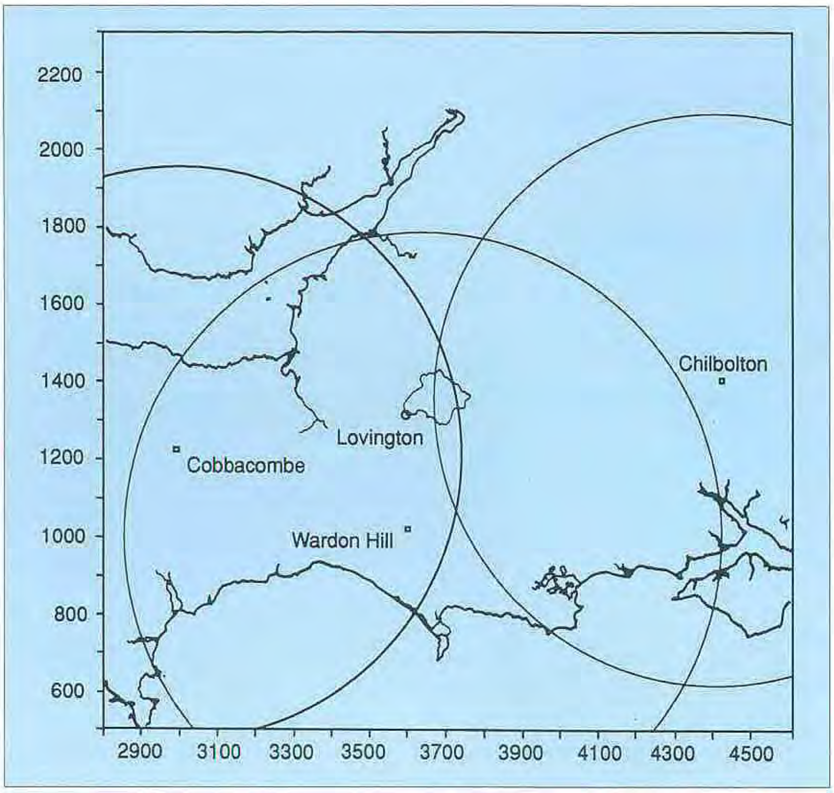


Figure 51 *The Brue catchment used in the HYREX study and the associated scanning radars (75 km radar circles indicated)*

The Brue catchment in Somerset, draining an area of 135 km^2 to Lovington, will provide a focus to HYREX. A dense network of 53 raingauges is planned for completion towards the end of 1993; an automatic weather station has also been installed. The catchment is scanned by three radars (see Figure 51): a new Doppler C-band radar at Cobbacombe Cross, a conventional C-band radar at Wardon Hill and an experimental Doppler dual-polarisation S-band radar at Chilbolton. A mobile vertical pointing X-band radar operated by the University of Salford will also be deployed within the catchment.

The Institute, in collaboration with the Joint Centre for Mesoscale Meteorology, is developing a high resolution rainfall model for very short-term forecasting based on simple cloud dynamics and incorporating radar, Meteosat, synoptic climate and radiosonde data. A second study at IH is addressing radar/raingauge network design issues and rainfall field structure as it affects hydrological response at the catchment scale. It is expected that a more fundamental understanding of radar rainfall measurement, rainfall field structure and flow response to rainfall will result from these HYREX studies over the next three years.

1992/93 — A reminder of the UK's vulnerability to hydrological stress

The impact of the very unusual weather patterns which have characterised much of the recent past has helped re-focus attention on many of the issues at the heart of hydrological research, and its practical application, in the United Kingdom. 1992/93 provided a clear demonstration of our continuing vulnerability to drought and floods. Man's ability to exacerbate as well as ameliorate their effects on both the community and the aquatic environment underpins the requirement for improved engineering design procedures and water management strategies. This need is given a greater emphasis by the possibility that the clustering of atypical hydrological events in recent years may signal a continuing period of climatic instability.

River Kennet near Avebury (Photo: Neil Campbell-Sharp)

Hydrological monitoring - a prerequisite for decision making

The Institute of Hydrology and British Geological Survey jointly operate a national hydrological monitoring programme on behalf of the Department of the Environment and the National Rivers Authority. It provides an important input to policy development and a valuable stimulus for research initiatives. As part of the programme, initiated early in 1989 as a response to developing drought conditions, reports on rainfall, river flows, groundwater levels and reservoir contents throughout Great Britain are published monthly* (see Figure 52). The reports form the basis of a range of briefing notes, articles and technical papers aimed at increasing scientific and public awareness of hydrological and water resources issues. Data held on the National River Flow Archive (IH) and National Groundwater Level Archive (BGS) provide the historical perspective within which the severity of droughts or flood episodes can be assessed; both archives are component databases in the National Water Archive.

Figure 52 *Hydrological Summary for Great Britain*

** Copies of these reports are available on subscription - £48 per year - from the National Water Archive Office.*

The drought

The remarkably protracted drought which at one time or another affected much of western Europe, can be traced back to the spring of 1988 in some eastern areas of England. In meteorological terms, the UK drought achieved its greatest severity during the early spring of 1992. For England and Wales as a whole, rainfall over the two years beginning in March 1990 was remarkably low: only in 1932-34 have similar nationwide rainfall totals been recorded this century. Marginally drier conditions also occurred in the 1850s and (more conjecturally) in the 1780s. Generally, the drought increased in intensity in a south-easterly direction. For some districts in East Anglia, accumulated rainfall deficiencies over the period from the summer of 1988 to the spring of 1992 were the equivalent of a full year's rainfall.

Rainfall shortages of this magnitude inevitably produce considerable water resources and environmental stress. But the 1988-92 drought was set apart from its precursors by the outstandingly high evaporation losses (see Figure 53) which characterised what was the warmest five-year sequence in the 334-year Central England Temperature series. For lengthy periods evaporation demands in southern Britain were typical of the rates normally associated with central France. Their effect was to translate a rainfall deficiency of around 20% into a reduction in replenishment to the Chalk aquifer of well over 50%. Groundwater provides the bulk of the summer flow in many lowland rivers and the protracted decline in runoff was accompanied by a shrinkage in the stream network which is without modern parallel. The corresponding loss of amenity and aquatic habitat, albeit temporary, was considerable and the ecological consequences have still to be fully assessed. Spring failures and dry winterbournes were widely encountered in areas where the impact of abstractions on runoff is very modest but the drought's effect was certainly accentuated in those catchments where groundwater pumping, often over many years, had depressed water-tables and caused headwater sources to migrate downstream.

Through artificial augmentation (e.g. using groundwater, inter-catchment transfers or sewage effluent) and other means such as demand restrictions, water management makes a major contribution to the maintenance of low flows during drought periods. However, the scale of the challenge represented by a sustainable water resources development target may be judged by the recent diminution of runoff rates in what is already the driest part of the country. For many East Anglian rivers, summer flows which would be expected once every 25 years (on average) on the basis of pre-1989 data, now have a recurrence frequency of once or twice a decade.

Rainfall was generally above average in the spring of 1992 but, in the lowlands, arrived too late to be immediately beneficial in water resources terms. The bulk of the rainfall was accounted for by accelerating evaporation demands and, following a barely discernible upturn over the winter in parts of the Chalk, groundwater levels continued to decline gently (Figure 54). By the late summer overall groundwater resources in England and Wales appeared, on limited evidence, to be at their lowest since the turn of the century. The unprecedented low level of aquifer replenishment over the 1988-92 period, around half of the preceding four-year minimum in parts of the eastern Chalk, prompted a review of reliable groundwater yields and stimulated research directed towards the more effective assessment of areal recharge, particularly in those regions where annual rainfall and evaporation totals are broadly comparable.

Humberside		Lower Thames Valley		Devon	
Year	*PE (mm)*	*Year*	*PE (mm)*	*Year*	*PE (mm)*
1990	721	1990	742	1990	666
1989	695	1989	731	1989	662
1976	650	1976	672	1984	627
1992	640	1992	647	1975	615
1991	622	1991	637	1976	605
1970	617	1984	627	1980	604
1986	617	1970	612	1992	592
1975	616	1988	612	1961	587
1982	608	1967	598	1985	583
1967	607	1986	598	1988	583
1964	606	1969	594	1983	582
1984	606	1985	591	1977	577
1961	597	1983	588	1982	575
1988	594	1961	586	1966	573
1983	591	1975	586	1973	566
1974	583	1964	583	1962	565
1977	581	1973	578	1970	562
1985	579	1974	578	1987	560
1981	577	1982	575	1991	559
1965	572	1966	571	1967	558
1962	567	1972	565	1965	557
1966	567	1987	565	1986	555
1980	566	1971	561	1969	555
1963	566	1965	558	1964	554
1979	561	1968	554	1981	552
1971	556	1962	551	1979	550
1973	552	1963	551	1978	550
1987	550	1980	549	1968	540
1968	546	1977	536	1963	538
1978	541	1979	531	1972	536
1969	540	1978	514	1974	511
1972	528	1981	506	1971	505
Av.	591		589		572

Figure 53 *Ranked annual potential evaporation (PE)*

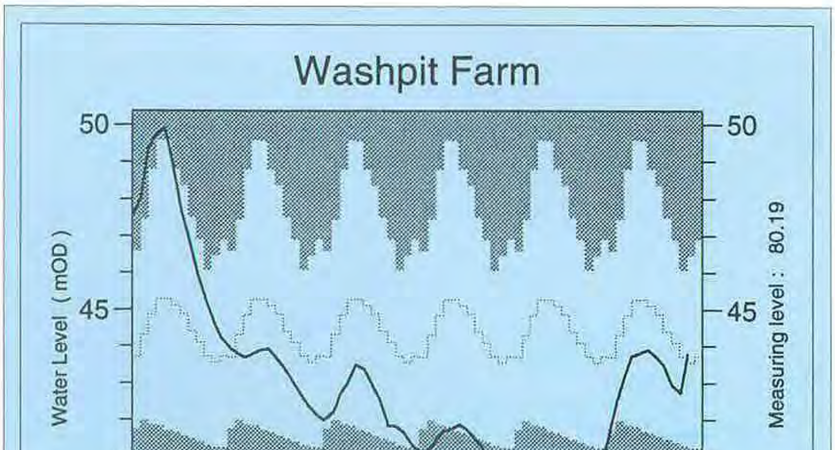


Figure 54 *Groundwater levels in the Norfolk Chalk 1988-93.*

The drought, over its full compass, was most severe in those parts of the UK with the lowest rainfall. These are generally also the areas with the highest concentrations of population, commercial activity and intensive agriculture, together generating the fastest growing water demand. Other regions of high population density and limited rainfall may readily be identified throughout Europe, but most of them benefit, via international river systems, from heavy precipitation in (often remote) headwaters. This is the case in the Netherlands, the Ruhr in Germany, and the North Italian Plain where rivers draining from the Alps provide a substantial supplement to the indigenous resources. The drainage pattern in England is less favourable for naturally augmentating resources in the lowlands: the narrowing margin between water demand and supply implies a fundamental and unique geographical fragility at times of low rainfall.

The transformation

Any post-drought recovery was clearly going to be protracted, and probably very uneven, given the need to generate rises in groundwater level from an exceptionally low base. In the event, a relatively wet summer in 1992 produced moist lowland soil conditions by the early autumn and raised the prospect of a substantially extended winter recharge season. Very unsettled weather conditions, including thunderstorms on the night of the 22nd September (which produced more than the monthly average rainfall over much of the drought affected area), generally arrested the recessions in groundwater levels, and in some districts initiated a very brisk start to the seasonal recovery. Thereafter, sustained rainfall over the final quarter of the year produced exceptionally rapid rises in groundwater levels. The steep recoveries echoed the terminal phases of the 1959, 1976 and 1984 droughts and suggested a common causality, but the 1988-92 drought was certainly a more complex event than the much shorter rainfall deficiencies which preceded it.

By early December 1992, the focus of hydrological concern had shifted to the threat of flooding, as heavy frontal rainfall on saturated catchments produced widespread floodplain inundations.

Figure 55 *Flood damage near Dalguise (Tayside) in February 1990 (above) and again in January 1993 (right)*

The floods

Notwithstanding the relative dryness of some eastern districts in 1992, Scotland registered its second highest annual rainfall total in a 125-year record; 1990 was considerably wetter, however. In common with parts of Scandinavia, the recent past has witnessed exceptionally high runoff from many mountainous catchments. Winter runoff, from the Highlands in particular, has shown a tendency to increase over the last 20 years and spate conditions have been common in the 1990s so far.

Over the post-1988 period the most outstanding of a number of notable flood events occurred in mid-January 1992, following blizzard conditions which left large accumulations of snow across much of central and northern Scotland. The passage of successive warm fronts, with associated rainfall, triggered a swift thaw which produced very rapid increases in flows in Highland rivers. Record peak flows were recorded at Balquhidder in the Trossachs, where the Institute of Hydrology's experimental catchments provide a unique opportunity to study the complex processes governing upland flood propagation under such circumstances.

By the 16th January, rivers draining most tributaries of the River Tay were in flood; on the following day, the Ballathie gauging station recorded a daily mean flow of almost 2000 cumecs, surpassing the previous highest on the National River Flow Archive. Hundreds of properties were flooded, mostly in Perth where the Tay rose to its highest known level since 1814, floodplain inundation was very extensive and there was severe disruption to transport.

Particular attention was directed to this very damaging flood episode because only three years had elapsed since the last major flood on the Tay.

The relatively close juxtaposition of two outstanding flood events — both comfortably surpassing the previous highest in a record from 1952 — has greatly reduced the expected frequency of events which were hitherto considered very rare (Figure 56). Figure 57 suggests that the return period of a 2000 cumec flood has reduced to around 100 years. Significant variations in return periods with increasing record length are to be expected but changes of this magnitude illustrate the sensitivity of flood frequency analyses to extreme events, even when using comparatively long flow records.

Increased flooding in Scotland and the lowland drought in England are manifestations of the greatly accentuated rainfall gradient across Britain which has been a feature of most of the last five years. This, together with the elevated temperatures and exceptional evaporation rates over the 1989-92 period, exhibits a degree of consistency with some favoured — but still tentative — climate change scenarios. However, UK weather patterns are inherently capricious and the recent extensions in the recorded range of runoff and recharge rates are insufficient to establish any firm trend towards new climatic territory. The effect of any such trend on flow regimes is likely to be accentuated or masked by changes in land use or patterns of water exploitation. This serves to re-emphasise the importance both of hydrometric measurement and hydrological research in providing the scientific foundation upon which innovative and environmentally sensitive water management strategies can be developed.

Period of Record *(Ballathie gauging station)*	No. of Annual Maxima	100-year flood *(m^3s^{-1})*	Return period for 2000 m^3s^{-1} flood *(yrs)*
1952-89	38	1540	>1000
1952-93	42	1990	105

Figure 56 *Variation in flood quantiles for the River Tay with the inclusion of recent data*

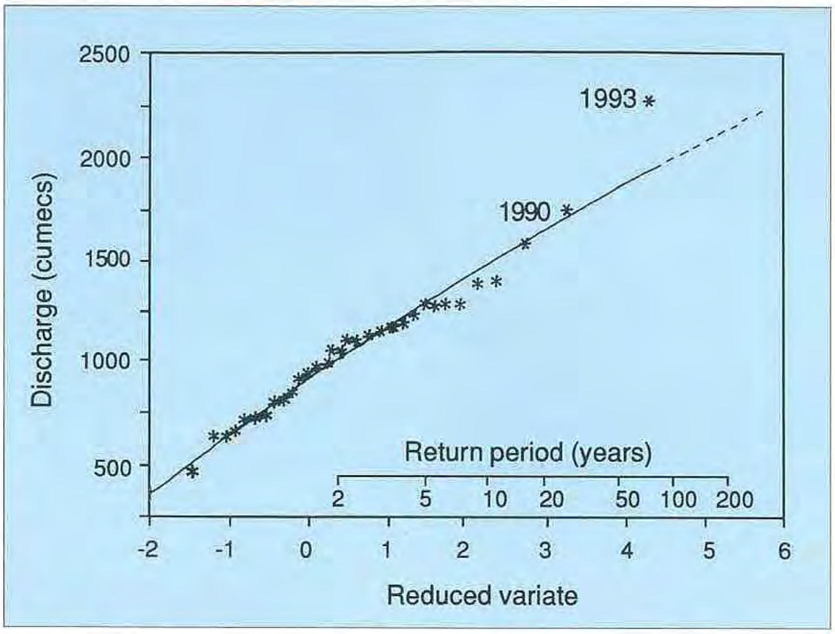


Figure 57 *Flood frequency curve for the River Tay at Ballathie for 1952-93*

Hydrological software — a new vehicle for technology transfer

The Institute of Hydrology wants its research findings to be used as widely as possible. We aim to transfer appropriate scientific expertise and knowledge to a wide range of academic, industrial and Governmental users. For many years hydrological instrument development has placed the results of IH research into the hands of practitioners and other researchers.

Automatic Weather Stations, multi-sensor hydrometeorological equipment to give direct measurement of evaporation and a wide range of systems for improved measurement of water in soils have been produced. Now the Automatic Weather Station concept is being extended to provide an Automatic Soil Water Station, an advance made possible by the development of a reliable capacitance method which determines soil moisture by measuring the soil's dielectric constant.

One new route for promoting the results of hydrological research is through the production and sale of original software. Previous Annual Reports have recorded the development, by IH and ICL jointly, of a complete system of hardware, software data and services to serve advanced data-handling requirements of major water industry players. Smaller software packages, suitable for a wide range of operational and training purposes but aimed at the microcomputer user, have also been prepared with great success. Products chosen for the market place are developed within a quality management system, to achieve a software tool best suited for hydrological practitioners. Hydrological knowledge developed in the Institute is thereby transferred to many outside organisations through each software product, encouraging its use in engineering, planning and education.

A Hydrological Software group was formed in 1989 specifically to explore the development of user-friendly, attractive software packages for microcomputers, encapsulating scientific methodologies and techniques researched at the Institute. Since its formation the Hydrology Software section has succeeded in transferring products to over 500 outlets; in this process it has generated £500,000 for improvements and new software development. The provision of software has instigated a two-way communication with users and has stimulated a transfer of ideas back to the Institute including areas for further research.

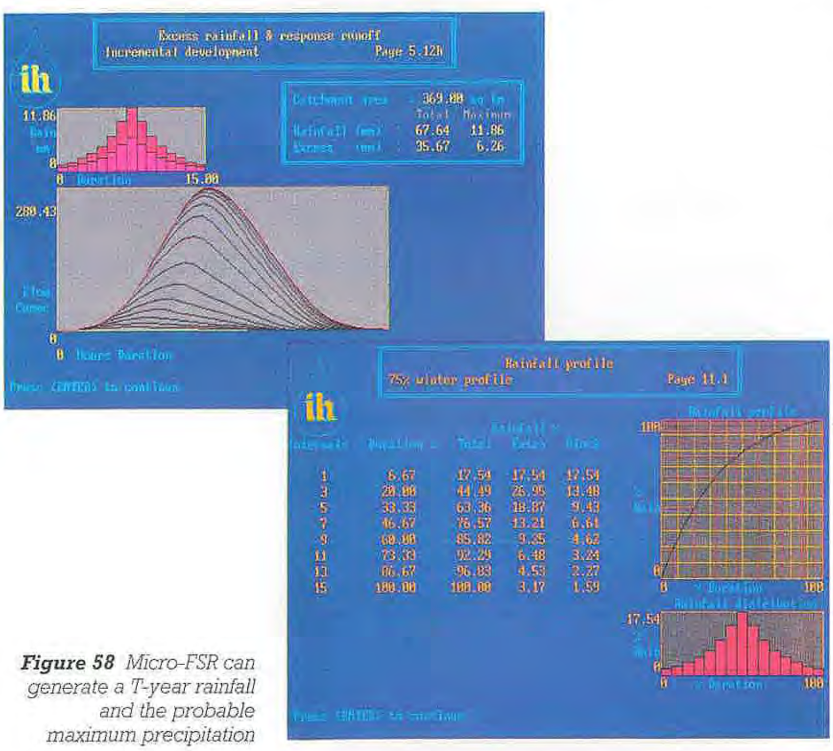


Figure 58 *Micro-FSR can generate a T-year rainfall and the probable maximum precipitation*

Six major software packages make up the portfolio of 1992/93 Institute of Hydrology Professional Software products. These are:

- HYDATA — a Hydrological database and analysis suite of programs
- HYFAP — an annual maximum frequency analysis program
- HYRROM — a conceptual rainfall runoff model
- Micro-FSR — a design flood estimation program
- QUASAR — a DEC VAX-based water quality model
- GRIPS - a groundwater information processing system

The existing software packages are supported through a help desk, and are maintained with a programme of development to expand the scientific functionality, and to improve user interfaces to keep pace with the industry standards.

1992 saw the release of version 2 of Micro-FSR, providing users with an updated computer-based package for implementing the design flood estimation methods described in the *Flood Studies Report* and subsequent supplements, originally published by the National Environment Research Council in 1975. This new version of Micro-FSR incorporates new sections to include the routing of a hydrograph through a reservoir for spillway design, and sediment routing through a balancing pond. Figure 63 shows some screen captures of Micro-FSR v2.0.

A new version of HYDATA and several utilities to aid data transfer have been developed. An upgrade to HYTRAN has improved this particular utility to help transfer data from many outside sources automatically into HYDATA. HYNWA enables the provision of data from HYDATA to the National Water Archive at IH, providing a batch option to help those wishing to transfer information on a regular basis. HYDATA is now at the core of the National hydrological archive in nine countries with additional regional and project based databases.

This year, ODA have supported provision to the SADC countries of Africa in pursuit of a standardised data collection process, to underpin regional hydrological research. By the end of 1995 it is expected that HYDATA will be available throughout most of Southern and Eastern Africa as the National Water Archive. The map (Figure 64) outlines areas of the world using HYDATA.

IH is actively developing new software for water quality database and modelling systems in response to the needs of the UK water industry. During the year staff developed and installed a prototype water quality database in Papua New Guinea. The database was configured to facilitate data management to local requirements, and training was provided for the Bureau of Water Resources in its use. The newly developed database runs on PCs under Windows 3.0 and 3.1, and has the ability to store all types of water quality information.

The powerful graphics facilities in HYQUAL make this program very user-friendly so that it can be used to organise and present water quality data in a manner which is easily assimilated by non-technical managers. Now that HYQUAL is available in Papua New Guinea, the potential for carrying out adequate studies of water quality is available for the first time. The installation of the database also provides a stimulus to collect more data in a systematic manner, thus providing a better understanding of the significant water quality problems facing that country.

In January 1993 IH held its first Software Open Day. This was intended to provide current users, and other interested parties, with the opportunity to investigate the full range of professional software products at first hand. Over 100 visitors saw demonstrations of the software, and discussed the underlying hydrological principles in workshop sessions. There was also the chance to provide input to future software developments through discussion of scientific requirements, and to preview software soon to be released.

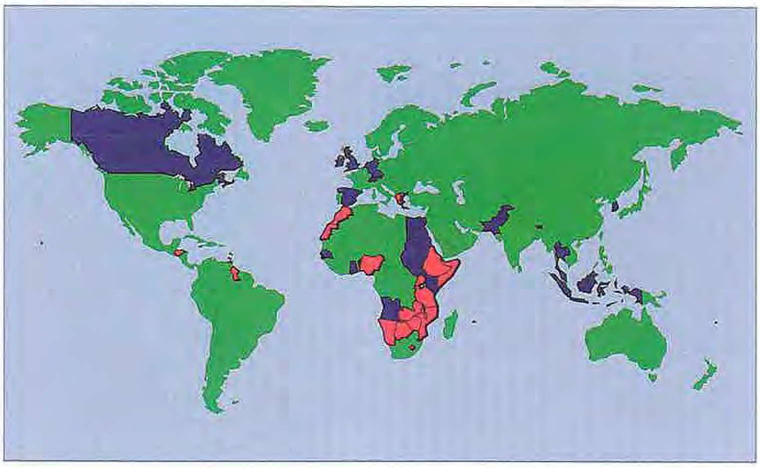


Figure 59 *HYDATA worldwide: the red areas are national water archives and the blue show project or regional databases*

The day proved to be very successful with a wide range of interesting and useful suggestions from our visitors, including offers of 'beta' testers for new software (i.e. volunteers to test new software in an operational environment), and discussion and solution of user's problems 'on the spot'. It was also a golden opportunity for visitors to examine the suitability of the packages for novel hydrological applications and to discuss their use with the scientist supporting the product.

Training, aimed at providing new owners of hydrological software with an understanding of its operation and a detailed knowledge of the underlying hydrology encapsulated within, ensures the most appropriate use. Several training courses have been run, particularly in support of users in the UK water industry (see Appendix 8).

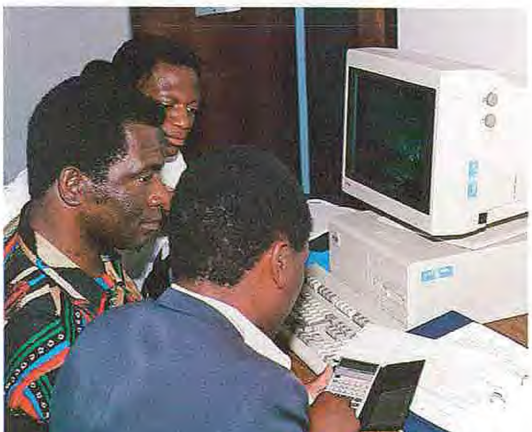


Figure 60 *Training was given at a workshop in Nairobi, funded by WMO and ODA, in the use of databases for hydrological information and analysis to a postgraduate hydrology course aimed at senior practising hydrologists.*

The Land-Ocean Interaction Study — a new NERC initiative

The links between the terrestrial and marine environments are the focus of a major new NERC initiative, the Land-Ocean Interaction Study (LOIS). The Institute of Hydrology has a major role in this five-year collaborative multi-disciplinary programme. Very little is known about the flux of materials from British rivers into the seas as the lower ends of our river systems have not been extensively instrumented for measurement of flow or water quality. For instance, accurate estimations of sediment output from large British rivers are not yet possible. Similarly, little is known of the chemistry of the material and the transformations which occur in transport from freshwater to saline systems. However, many of the pollutant problems in coastal areas relate to land-derived contaminants which are conveyed to the coast by river systems. Improved understanding of past and present transport will also make possible the development of large-scale river basin models to predict the impacts of natural and man-made environmental changes over the next 50-100 years.

The overall objectives of LOIS are

- To characterise and measure the fluxes of energy and materials into the coastal zone from river basins, the atmosphere and ocean;
- To identify and quantify the physical, chemical and biological processes which govern these fluxes;
- To provide a long-term perspective of these fluxes through the Holocene;
- To initiate the development of coupled land-ocean models to predict impacts of environmental change.

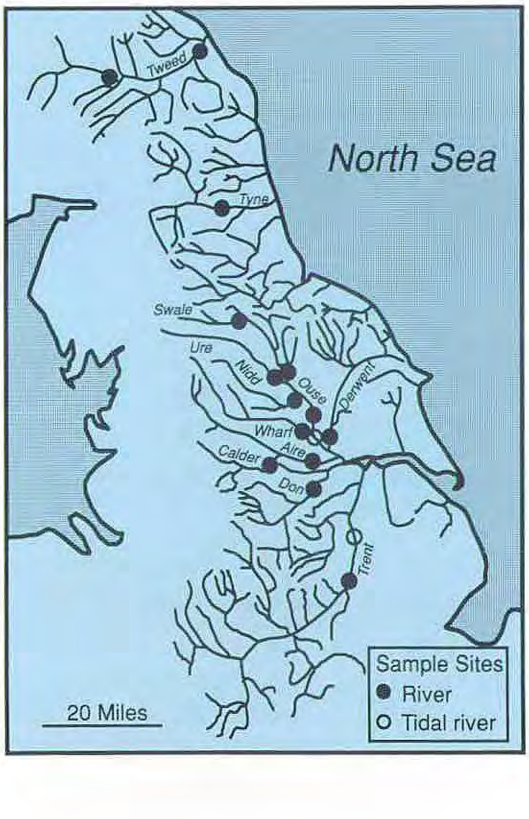


Figure 61 *The LOIS river basins study area showing major field monitoring sites*

LOIS began in early summer 1992. The programme is a significant UK contribution to the International Geosphere-Biosphere Programme (IGBP) and Land-Ocean Interactions in the Coastal Zone (LOICZ). This report summarises the main activities which make up the river research within LOIS. Until now hydrological, sediment, chemical and biological research studies have usually been carried out separately. LOIS will integrate this research more than has ever been possible before. For the first time, intensive and coordinated monitoring will be carried out on a wide range of substances, moving down through river basins to estuaries and the coast. This opens up an important new scientific opportunity: to obtain mass transport figures for British rivers. It will be possible to link hydrological, sediment and pollution events routinely for the first time. Similarly, detailed data collection will enable scientists to validate a range of hydrological models to determine fluxes and how they will alter with changes in land use, industrial inputs or climate.

The core study area comprises the catchments of the east of England with a particular focus upon the Humber system and the Tweed. The study area has a combined freshwater catchment area of more than 42,000 km². The Humber catchment, approximately 24,000 km², is the largest of any UK estuary. The Humber system also contains 20% of the UK population and a very significant part of energy, industrial and agricultural production, a fact reflected in the quality of the freshwater discharges to the North Sea.

With regard to the study sites, the Yorkshire Ouse will be the most intensively studied river. The other principal rivers contributing to the Humber are also covered by monitoring stations in their lower reaches. In some cases there is a need for ultrasonic gauging at the river/estuary interface, mostly for short-term deployments (often associated with intensive estuarine studies) because the river outputs to the Humber estuary are very complex. There is a multiplicity of major rivers with large-scale water transfers and effluent inputs. The Tweed has been chosen as the other area of intensive study, because of its contrasting geomorphological and water quality characteristics: there is close collaboration with the National Rivers Authority and the Tweed River Purification Board.

Continuous, event-related and routine field monitoring has begun at existing and newly constructed flow gauging stations. To determine movement of materials from river basins, the following measurements are being made:

- Hydrological — principally river water discharges;
- Sediment — mainly suspended sediment; physical characteristics, such as particle size distribution, in addition to chemical and biological properties;
- Biological — live and dead organisms (phytoplankton, bacteria, macrophytes)
- Chemical — major ions, pH, alkalinity, nitrogen, silicon and phosphorus compounds, dissolved and particulate organic carbon, iron, manganese and aluminium;
- Contaminants — selected heavy metals, representative pollutants from among microorganisms.

In collaboration with other research institutes and universities, river conditions are being investigated: the sources and delivery of material to the channel, within-channel storage and transformations. Remote sensing and catchment modelling using hydrologically-driven catchment-wide and channel-based models will be integrated, partly within existing Institute of Hydrology GIS systems. This work will be related to the long-term perspective provided by geological studies and very closely linked to the LOIS estuarine and coastal research. Some of the important elements of this programme are described in further detail below.

Figure 62 *A Landsat image showing the lower reaches of Humber rivers, estuary and adjacent North Sea*

Sediment transport studies

Most British river sediment studies have been carried out on small-scale upland catchments, predominantly in the West of Britain. The required intensity of systematic flow-related measurement of sediment flux from a large number of large-scale catchments in close proximity to estuarine and coastal systems has not been carried out before. The study of substances (such as contaminants) which attach to the particulate matter is at an early stage. Interactions between biological and physical dynamics are also not well understood. These important scientific questions are being addressed by LOIS.

Water chemistry monitoring

A wide range of elements is being monitored. This permits the chemical fingerprinting of hydrochemical processes and the understanding of linkage and separation between hydrological, sediment transport, inorganic and biological controls. Partition between dissolved and particulate phases is extremely important in modelling the processes along the river systems and in describing fluxes to estuaries. Routine monitoring is expected to provide new information about spatial and temporal changes in element compositions, whether in solution or adsorbed onto sediment particles. This is one of the few opportunities for a field sampling programme to be intimately linked to modelling requirements: previously, modelling work has often had to make do with chemical information collected for other reasons (e.g. for water quality consents).

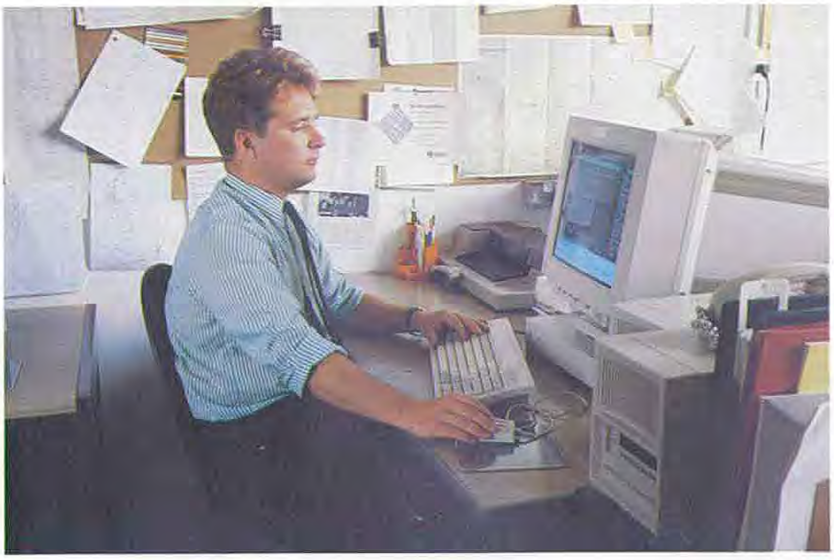


Figure 63 *Use of the WIS database in the LOIS river basins datacentre*

The database, remote sensing and GIS

The LOIS programme will require — and will generate — very large data sets. A LOIS River Basins Datacentre has been established at the Institute. This centre will contain data on time series chemistry, hydrology and meteorology for the East Coast rivers. It will also hold extensive spatial databases such as the digitised river network, HOST (Hydrology Of Soil Types) and land use data. With this information it will be possible to establish dynamic models which also take account of spatial variability.

The GIS system ARCOINFO will be used to manipulate spatial databases and the IH Software System WIS will manage the total database. These data management techniques provide powerful tools for model development. They also provide the means for LOIS researchers in other institutes and universities to access the data and the model simulation results.

Remote sensing of land cover and river corridors will be carried out using an advanced Compact Airborne Spectrographic Imager system (CASI) dedicated to the LOIS programme. It is anticipated that the experience and knowledge gained will help considerably to advance the interpretation of remotely-sensed river imagery.

The integration of the intensive field programme data with other databases within a Geographical Information System (GIS) framework will be unique at the temporal/spatial scales and resolution. The necessary links between research institutes, universities and the NRA to integrate data from the core study area, will be more extensive and complex than ever before attempted for British river basin research.

Integrated modelling

Given the complex, dynamic and multidisciplinary nature of the LOIS project it is inevitable that models will play a major role. Models allow an assessment of the processes controlling dynamic behaviour and will be operated at a number of different time scales.

The objectives of the modelling are

- to identify the catchment-scale hydrological and other controls upon flux of water and associated materials to channels;
- to understand the processes controlling the behaviour of key water quality determinands, sediments and biological systems;
- to assess the impacts of land use and climate change upon river flows and water quality;
- to provide simulated time-series data for river flow and water quality from river to estuary/ coastal systems.

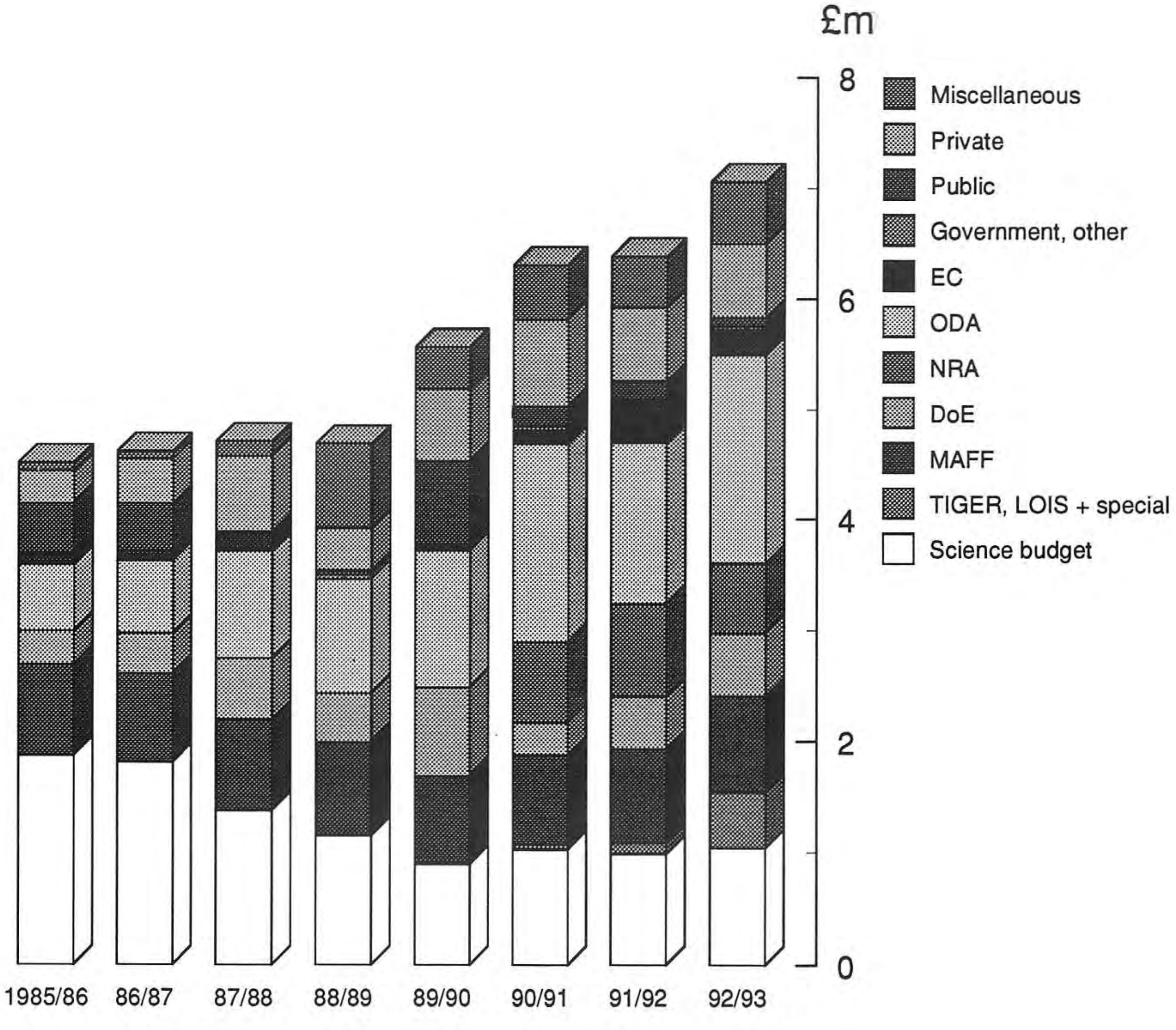
LOIS integrated model development is building upon existing IH expertise in hydrological and water quality modelling. Models developed within individual process studies will be combined with channel and distributed models to produce an integrated model which links spatial and temporal databases, within a GIS format, compatible with model development in the estuaries and coasts components of LOIS. The large volume of wide-ranging time-series data will provide an opportunity for integrated model development at spatial scales not previously attempted in the UK.

The broad range of catchment types included in the core programme will permit spatial extrapolation of the modelling to many other British river basins. The historical reconstruction and predictive capabilities, built up from advanced process understanding at a range of spatial and temporal scales, will also be an innovative development.

Appendix 1 Finance

Sources of income

The histogram shows the sources of the Institute's income over the past eight years, adjusted to 1992/93 prices.



Appendix 2 Staff list as at 30 September 1993

Prof W. B. Wilkinson, PhD
Director

V. Lynch
Personal Secretary

HYDROLOGICAL PROCESSES

J. S. Wallace, PhD
Divisional Head

A. D. Spencer
Personal Secretary

Global Processes
J. H. C. Gash, PhD
- micrometeorology
R. J. Harding, PhD
- hydrometeorological modelling
C. R. Lloyd, BA
- evaporation research
I. R. Wright, BSc
- micrometeorology
E. M. Blyth, MA
- climate modelling research
A. D. Culf, PhD
- boundary layer meteorology
C. Huntingford PhD
- evaporation modelling
C. M. Taylor, MSc
- mesoscale modelling research

Vegetation and Sub-surface Processes
J. M. Roberts, PhD
- plant physiology, transpiration
J. Bromley, PhD
- groundwater resources
M. G. Hodnett, BSc
- soil water fluxes and crop water use
R. Ragab, PhD
- soil physics
C. J. Holwill, PhD
- evaporation from semi-arid vegetation
S. J. Allen, PhD
- evaporation from semi-arid vegetation
N. A. Jackson, MSc
- water use in agroforestry systems
A.-L. C. McWilliam, PhD
- tropical vegetation gas exchange

Land Use and Water Efficiency
Prof I. R. Calder, PhD
- environmental physics; Hydrological Adviser to ODA

M. Robinson, PhD
- soil water studies; streamflow generation
J. D. Cooper, BSc
- unsaturated soil water flux studies
A. J. Dixon, BSc
- drilling and groundwater monitoring
H. M. Gunston, BSc
- tropical agricultural hydrology; ODA Coordinator; Training Officer
R. L. Hall, PhD
- evaporation modelling
H. G. Bastable, PhD
- forest climatology
S. A. Boyle
- soil hydrology
P. T. W. Rosier
- soil moisture & transpiration studies

Remote Sensing
J. B. Stewart, PhD
- evaporation and radiation studies
G. Roberts, PhD
- remote sensing/surface hydrology
D. S. Biggin, BA
- microwave and thermal studies
K. Blyth, MPhil
- microwave remote sensing
J. W. Finch, PhD
- groundwater and GIS

ENVIRONMENTAL HYDROLOGY

P. G. Whitehead, PhD
Divisional Head

J. A. Champkin
Personal Secretary

Water Quality Systems
A. Jenkins, PhD
- hydrochemical modelling, acid deposition
A. Eatherall, PhD
- environmental modelling
W. T. Sloan, MSc
- environmental modelling
C. L. Shaw, MSc
- acid deposition
C.E.M. Sefton, BEng
- environmental modelling
R. J. Wilkinson
- modelling *E. coli* in streams
S. Tolchard
- assistant

Agrohydrology
C. H. Batchelor, PhD
- irrigation studies, crop water use
C. J. Lovell, PhD
- soil and water conservation
R. J. Williams, BSc
- water quality modelling
A. C. Johnson, PhD
- environmental microbiologist
A. Haria, BSc
- soil physics
P. C. R. Volkner, BA
- water quality catchment studies
V. Cruxton, BSc
- soil moisture studies

Hydrological Modelling
R. J. Moore, MSc
- hydrological forecasting, weather radar, stochastic hydrology
D. A. Jones, PhD
- stochastic hydrology & forecasting
A. Calver, PhD
- hydrological analysis & distributed modelling
D. M. Cooper, PhD
- distributed modelling, stochastic hydrology
R. M. Austin, MSc
- hydrological forecasting and control
V. A. Bell, BSc
- distributed forecasting
D. S. Carrington, MPhil
- weather radar studies
D. R. Lewis, PhD
- distributed modelling

Hydrochemistry
C. Neal, PhD
- chemical hydrology
C. J. Smith, LRIC
- analytical chemistry
C. L. Bhardwaj, PhD
- analytical chemistry

M. Neal, PhD
– chemical analysis, X-ray diffraction & mass spectrometry
A. J. Robson, BA
– mathematical modelling
H. A. Jeffery
– analytical chemistry
S. McCrorie
– analytical chemistry
M. L. Harrow
– analytical chemistry

Experimental Catchments

Based at Plynlimon
J. A. Hudson, BSc
– forestry impacts, catchment hydrology, hydrometeorology
K. Gilman, MA
– environmental impact, wetlands, mathematical techniques
G. J. L. Leeks, BSc
– TFSD LOIS programme manager; fluvial geomorphology, sediment studies
P. J. Hill
– field measurements; process studies
S. B. Crane, BSc
– hydrometeorological data
S. Hill
– laboratory management
W. A. Hughes
– network and site maintenance

Based at Stirling
R.C. Johnson, BSc
– catchment hydrology, snow studies, hydrometeorology, sediment studies
A. R. Black, PhD
– Scottish surface water archive
D. J. Price, MSc
– catchment management; forest hydrology
D. Hill
– assistant

ENGINEERING HYDROLOGY

F. M. Law, BSc
Divisional Head

S. J. Beresford
Personal Secretary

National Water Archive
M. L. Lees, BSc
– Archive manager
T. J. Marsh, BSc
– editor, *Hydrological Data UK* series
I. G. Littlewood, PhD
– water quality hydrologist
R. L. Hinton, MSc
– database programmer
S. C. Loader, BSc
– validation controller
S. Green, BSc
– user liaison and application
F. J. Sanderson, MSc
– hydrological monitoring; archivist
S. Black
– National Water Archive office
D. G. Morris, BSc
– Spatial Data Group manager; National River Flow Archive software coordinator
R. W. Flavin, BSc
– software developer; spatial data; National River Flow Archive
M. C. Clayton
– hydrologist
N. A. Rycraft, MSc
– spatial data manager
O. Swain
– software developer; National River Flow Archive; spatial data

Hydrologic Geographical Information Systems
R. V. Moore, MSc
– digital mapping & information systems
M. I. Allchin, BSc
– WIS technical manager
C. D. Watts, MSc
– ICL Research Fellow
C. I. Tindall
– Water Information System trainer

Flow Regimes and Environmental Management
A. Gustard, PhD
– Water resource studies and international flow regimes
A. Bullock, PhD
– low flows
I. W. Johnson, PhD
– environmental management
H. G. Rees
– European data base manager
A. R. Young, MSc
– Micro-Low Flows
A. J. Andrews, BSc
– low flows & environmental management
J. M. Dixon
– hydrologist; Welfare Officer
C. R. N. Elliott, BA
– environmental management: field studies
K. M. Irving, BSc
– environmental hydrologist (artificial influences)
A. E. Sekulin, MSc
– consultant programmer

Flood and Storm Hazard
D. W. Reed, PhD
– hydrological extremes
D. C. W. Marshall, MSc
– engineering hydrology
E. J. Stewart, MSc
– rainfall studies; HYREX
I. J. Dwyer, MSc
– mathematician
A. C. Bayliss, HND
- flood analysis
T. K. M. Jones, BSc
– hydrology

Catchment Distributed Modelling
P. S. Naden, PhD
– hydrological modeller
T. Spijkers, MSc
– rainfall-runoff modeller
S. M. Crooks
– applied hydrologist
P. Broadhurst, MSc
– hydrologist
B. Gannon
– hydrologist

Climate Change Impacts
N. W. Arnell, PhD
– water resources impacts, regional hydrology
N. S. Reynard, MSc
– hydrometeorologist

APPLICATIONS RESEARCH, POLICY STUDIES & INFORMATION

A. G. P. Debney, BSc
Divisional Head;
Assistant Director

B. A. Hawker
Personal Secretary

Water Resource Systems
F. A. K. Farquharson, MSc
– overseas contracts, flood estimation
R. B. Bradford, MSc
– groundwater resources management
J. R. Meigh, PhD
– water resources and flood estimation
N. R. Runnalls, MSc
– marketing coordinator
K. J. Sene, PhD
– hydrological modelling, evaporation estimation
H. A. Houghton-Carr, MSc
- flood estimation; real-time flood forecasting
M. P. McCartney, MSc
– water resources and flood estimation
V. J. Bronsdon
– hydrological assistant; cartographer

Hydrological impacts
J. R. Blackie, MSc
– catchment studies, land-use change

J. P. Moores, MSc
– water resources; hydrological impacts
A. J. Semple, MA
– environmental economist

Hydrology Software
Y. P. Parks, MSc
– engineering hydrology and software development
K. B. Black
– systems analyst
K. Down, BSc
– software development
J. Zhang, PhD
– software development
R. Alexander
– software development
J. R. Parker
– software documentation, sales & support
A. Matthews, BA
– software sales & support

Instrumentation
M. Turner
– instrument development
D. D. McNeil, BSc
– instrument development
M. R. Stroud
– instrument technician
M. E. Walker
– instrument technician
R. G. Wyatt
– instrument technician

Workshop
A. C. Warwick
– workshop manager
G. H. Walley
– instrument craftsman
J. P. White
– instrument craftsman

Information Services
C. Kirby, BSc
– public relations & publications manager

J. H. Griffin, MPhil
– production editor
H. K. Stevens, BA
– production editor
J. E. Manion
– assistant

Library
S. B. Wharton, BA
– librarian
D. S. Dolton
– library assistant
P. Moorhouse, BSc
- library assistant

IAHS Press
P. J. Kisby
– manager

S. A. Cage, BSc
– assistant editor
P. J. Gash
– book orders

ADMINISTRATION

A. D. R. Gray
Head of Administration

Financial Management
H. M. Wood
– Finance Officer
A. M. Davies
– management information systems

Finance and Accounts
L. Aspinall, BSc
H. G. Thomas
E. A. Ostler
T. A. Gibson
L. Ross, BA
A. Napper

Registry and Establishments
S. A. Fenton
P. M. Sanders
V. Lambeth

Switchboard and Reception
E. Younghusband

Typing Pool
J. Hornsby
S. Smith
S. J. Fairhurst
H. J. Turner

Site Services
J. R. Fraser
– site services
J. Spencer
– caretaker/groundsman
I. R. Standbridge
– carpenter
A. O. Escott
- electrician

Motor Transport
R. G. Drewett
– craftsman

H. V. R. Jones
– driver

Stores
J. H. Jones
– storekeeper

SANDWICH COURSE STUDENTS
H. Bigley – University of Luton
R. Brand – University of Luton
I. Brightman – University of Luton
E. Brown– Coventry University
A. Cole – Sheffield Hallam University
C. Coulson – University of Luton
M. D. Cranston – Sunderland University
O. Highway – Coventry University
D. R. Hill – Plymouth University
M. Hodgson – Coventry University
L. Kneeshaw – Sunderland University
N. Koria – Sheffield Hallam University
Y. O. Man – Sheffield Hallam University
S. P. McGrath – Reading University
M. Paskiewiczl – Plymouth University
S. J. Rollason – University of Luton
P. Ultsch – Oxford Brookes University

COMMUNITY SCIENCE

LOIS (Land-Ocean Interaction Study)
G. J. L. Leeks, BSc
- LOIS Programme Manager (based at Plynlimon)
G. P. Ryland, MSc
- analytical chemist (York Laboratory)
P. Wass, MSc
- hydrology & sediment transport (York Laboratory)

TIGER (Terrestrial Initiative in Global Environmental Research)

Seconded from IH
M. A. Beran, BSc
– TIGER programme manager; TFSD climate change coordinator

H. R. Oliver, PhD
– TIGER III coordinator
M. Howarth
– finance & administration
S. G. Austin
– secretary

Seconded to TFS Directorate, NERC
A. M. Roberts

Seconded to IUCN, Switzerland
M. C. Acreman, PhD

Appendix 3 Scientific output

(i) Scientific papers

Acreman, M.C. & **Boorman, D.B.** 1993. Flood frequency analysis of the Cul de Sac River, St Lucia, using joint probabilities of rainfall and antecedent catchment conditions. In: Gladwell, J S. (Ed.) Hydrology of Warm Humid Regions *IAHS Publ. No. 216*, 353-364.

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Culf, A.D. & **Gash, J.H.C.**, 1993 Long-wave radiation from clear skies in Niger: a comparison of observations with simple formulas *J Appl. Meteorol* **32** 539-547.

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Freeman, C , **Hudson, J.A.**, Lock, M A & Reynolds, B 1993 A field-based approach to investigating potential impacts of drought induced by climatic change on wetlands. In: Extreme Hydrological Events Precipitation, Floods and Drought. *IAHS Publ. No 213*. 151-156.

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(iii) Software development

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(iv) Instrument provision/installation 1992/93

The Instrument Section provides a wide range of data capture systems for the experimental activities of this institute and also, through an NERC Automatic Weather Station Pool, supports Higher Education Institutions undertaking hydrological research.

April 1992
Water quality flow proportional sampling system
Surface capacitance probe for Wellesbourne
HYDRA and AWS for IH meteorological site
Surface temperature logging system for HAPEX-Sahel
Seven DCP systems for Brazil
New aspirated screen profile and PAR system for Brazil
Four Sigma-T systems for Niger

May
Four Sigma-T systems for Brazil
Water quality station at Rosemaund
Surface capacitance probe for Niger
Four AWS systems for TIGER HAPEX-Sahel
Four surface heat flux logging systems, TIGER HAPEX-Sahel

June
Four HYDRAs for Niger
Llyn Brianne flow gauging structure installed
Capacitance probe access tube installation equipment for Niger
ASWS-I at Newbury for ERS-1
ASWS-I at Cricklade for ERS-1
Monitoring system for forest road, Balquhidder

July
Two HYDRAs for Brazil
Interception gauges for Brazil
Automatic tensiometers for Wytham site
Runoff system for Wytham site
Manual tensiometers for Wytham site
Second surface capacitance probe for Zimbabwe
Three surface capacitance probes for Niger, ERS-1, etc.
Two surface capacitance probes for Brazil

August
HYDRA and AWS for Plynlimon
ASWS-II for National Rivers Authority

April-August
Eight NERC-pool AWS systems provided/installed

November
Two surface drains logging pressure transducers, Wytham
Pressure transducer and float system for stage back-up, Plynlimon
Four pressure transducer stage back-up systems, Plynlimon
Float stage back-up system, Plynlimon
Two surface capacitance probes and gravimetric kit, Kenya
AWS with downward Kipp and soil heat flux sensors, Plynlimon
Eighteen suction samples and eight in-field lysimeters, Wytham
Two pressure transducer tensiometer and gypsum block system, Wytham
Surface runoff, Wytham
45° access tube installation equipment
ASWS-II at Stanford-in-the-Vale for National Rivers Authority

December
Automatic tensiometer installation, Coventry
Logging system for deep tensiometers, Coventry
Surface water content in masonry, Building Research Establishment

January 1993
Second ASWS-II installation for NRA project
Modification to AWS loggers, Sri Lanka
Repair of automatic rainfall sampler unit, Plynlimon
Two pressure transducer tensiometer systems tested for installation at Rosemaund
Wytham pressure transducer tensiometer calibrated and tested for installation
Three NERC-pool AWS systems provided/installed
Logger and software provided for evaluation of electronic raingauge
Improvements in pressure transducer tensiometer system

February
Two conductivity/temperature/rainfall logging systems for Plynlimon
Two compact surface capacitance probes for trench measurement in Mauritius
Manufacture, calibration and testing of seven 1.2m pressure transducer tensiometers, Kenya
Preparation, calibration, testing and installation on met IRT and Bowen ratio logging systems for the BOREAS experiment in Canada
Manufacture of neutron probe installation equipment

March
Installation of AWS, river level and rainfall logging systems and access tube for capacitance probe, Jersey
Manufacture of 10 ASWS with three sensor arrays per station
Two SCIPs for ABRACOS project, Brazil

Abbreviations

ASWS = Automatic soil water station
AWS = Automatic weather station
DCP = Data collection platform
IRT = Infra Red Thermometer
PAR = Photosynthetically Active Radiation
SCIP = Surface Capacitance Insertion Probe

Prototype instruments are made in the Institute's well-equipped workshops

Appendix 4 Research projects

The Institute of Hydrology is a component body of the UK Natural Environment Research Council. Its science contributes to the integrated research programmes of the Terrestrial and Freshwater Sciences Directorate, involving four other institutes and several university units. IH research in 1992/93 comprised more than 180 directed and commissioned projects across six of the interdisciplinary programme areas of TFSD.

Programme 2 — Land Use, Agriculture and the Environment

Strathspey environmental research
Hydrological aspects of Environmental Assessment

Programme 3 — Global Environmental Change

Surface and boundary layer measurements, Sahel
Joint fluxes in tropical forests
Understanding SVATS for global modelling
Macromodelling (TIGER III)
Automatic weather station, Wytham site
Hydrological impacts modelling (TIGER IV)
Biome change as a climatic feedback

Tropical Rainforest Processes

ABRACOS: micrometeorology and climatology
ABRACOS: plant physiology and soils
ABRACOS: Tropical rainforest processes

Climate change

Impact of climate change on water resources
Extreme event hazard reduction
Impact of climate change on terrestrial ecosystems
Climate change and water resources in East Africa
Implications of climate change for the NRA
CLIMEX – climate change experiment

Programme 4 — Water Management and Hydrological Extremes

Land-river interactions

Physical habitat simulations in rivers (PHABSIM)
Ecologically acceptable flows
Habitat modification and instream flow requirements

Experimental catchments

Plynlimon water use
Effect of clear felling on upland runoff
Impacts of riparian wetlands on stream chemistry
Water resources and afforestation in Scotland
Fluvial geomorphology
Conservation management of wetlands
Effects of agricultural soil erosion on water courses
Hydrological evaluation of Cobbinshaw Moss
Erosion of forest roads
River Creed weir survey
Cairngorms Environmental Change Network
The protection of East Anglian wetlands

Catchment data

Plynlimon data water information system

Hydrological modelling

Physically based modelling, the IH Distributed Model
Système Hydrologique Européen (SHE) Model
Real-time forecasting of river flows
Distributed hydrological and hydrochemical models
Yorkshire river flow forecasting system
Variations in storm rainfall over London
Modelling nitrate leaching to surface waters
Weather radar and storm & flood hazard
White Cart flood forecasting system
Distributed flood forecasting models
Anglian flow modelling system
Development of improved methods of snowmelt forecasting
Radar software for Beckton/Crossness catchment model
RQFS: river quality forecasting system
Storms, floods and radar hydrology

Consultancy, UK

Minor repayment studies
Sub-surface exploration contracts
Cransley Lodge hydrological monitoring study
Impact assessment of proposed Roding barrage
Expert advice on floods
Disposal of PFA/FGD in mine/gravel pit workings, Nottingham, UK
Jersey catchment study
Jersey time series computation
River Roding fluvial/tidal flood study

Consultancy, Overseas

Future water supply strategy, APC Jordan
Support services for overseas repayment studies
Real-time flood forecasting - Hong Kong
North Yemen water resources master plan
Water balance of Lake Victoria
World Flood Study - Phase III
Review of Lesotho highlands Water Resources Division
Spring water survey, State of Qatar
Impact of small dams, Botswana
Sardar Sarovar project hydrology review

Surface Water Archive

UK surface water data
Water resources research progress
The 1989/90 Yorkshire drought - 1991 update
Modelling multiple wet season floods
IHACRES 1

Flood event modelling

Flood hydrograph estimation procedures
Representative basin database
Distributed model for UK application

Flow regimes

Flow regimes in Western Europe
Micro low flows
Land use and water resources in Southern Africa
Low flow estimation in artificially influenced catchments
Low flow estimation in the Philippines
Modelling faunal and floral response
European small hydropower atlas
Southern Africa low flows
Europe's environment, hydrological summary
Naturalised flows in Essex

Assessment of ecologically acceptable flow regimes
Botswana small dams

Storm hazards and hydrological extremes

Small catchment response, radar/water levels
Review of flood studies, statistical procedures
Rainfall extremes
Rainfall forecasts, Cameroon hydroelectric schemes
Joint probability study (reservoir safety)
Allowance for Discretization in Hydrological and Environmental Risk Estimation (ADHERE)
Bank-full return periods for Thames weirs
Rainfall frequency study: England and Wales
Rainfall-induced landslides
Flood response of large catchments

Hydrological software

Software development
HYDATA
HYRROM (hydrological rainfall runoff model)
GRIPS (groundwater information processing system)
QUASAR — VAX-version model
QUASAR — PC conversion
Micro-FSR
FFAP (flood frequency analysis package)
HYQUAL (water quality database)
Software training
Provision of QUASAR and DMM
HYDATA workshop
HYDATA for Uganda

Hydrologic Geographic Information Systems

Development of a hydrogeographic database
Water Information System
Redigitising the rivers of the NRA North West Region
Feasibility study digitising European (CEC) rivers

Agrohydrology

Mauritius drip irrigation: special studies
Small-scale irrigation schemes: collector wells
Soil physics drip irrigation: special studies
Management of limited water resources
Low-cost, high-efficiency irrigation
Agricultural chemical transport in soils and rocks
Irrigation using collector wells

Urban hydrology

Urban impacts on flood runoff
Urban runoff data collection

Programme 6 — Hydrological Processes

Regional scale modelling

FIFE
Regional scale surface energy balance
UK Meteorological Office joint development (MITRE)
International desertification experiment
A model of seasonal vegetation growth for GCMs

Dryland degradation processes

Plant physiological controls of evaporation
Hillslope flow process study: Zimbabwe

Environmental impact of trees

Broadleaf plantation in lowland Britain
Environmental implications of trees and land-use systems
Western Ghats forest project, India
Impact of eucalyptus plantations in Portugal
Water balance of African lakes
Land-use change, Upper Mahaweli catchment, Sri Lanka
Hydrological effects of short-rotation energy coppice

Semi-arid zone water balance

Hydrological atmospheric pilot experiment
Modelling regional scale evaporation, Sahel
Water use by vegetation in the Sahel
Arid zone recharge (SACRE)
HAPEX II - Sahel: soils
Remote sensing of semi arid regions
Water balance of agroforestry system on hillslopes

Surface and subsurface processes

Impact of flood protection on wildlife habitats
Stream hydrograph and storm runoff mechanisms
Monitoring of soil moisture for flood hydrology
Continuous monitoring of soil moisture for the NRA
Hydrology of shallow groundwater environments
Measurement of soil hydraulic properties
Wotton Rectory Farm groundwater investigation
Analysis of Coalburn catchment data

Remote Sensing

European Space Agency ERS-1 mission
Application of remote sensing to hydrology
ERS 1. microwave remote sensing in hydrology
Evaporation input for GCMs from satellite data
PC based system to use satellite data

Programme 11 — Freshwater Biology and Water Quality

Water quality

European network of catchments
Water quality modelling design & management
Pesticide pollution in catchments
Acid waters monitoring network
Organics in the aquatic environment
Modelling the effects of climate change
Critical loads of sulphur and nitrogen
Nepal research project
Modelling *E. coli* concentrations in streams
Acid mine modelling
Environmental change in ecosystems
Nitrogen module for MAGIC
Pesticide registration data, tria-sulphuron
Pollution dispersion along the Stour river

Hydrochemistry

Hydrochemical process studies
Forestry impact on upland water quality
Environmental isotopes
Identifying hydrological flow pathways, Spain
Biogeochemistry of a granitic catchment in southern France
Assessing hydrochemical flow pathways

Programme 13 — Scientific Services

Hydrological instrumentation

Capacitance probe
Automatic weather station
Field instruments
Maintenance and development of Hydra equipment
Soil laboratory
Investigation of moisture measurements in masonry

Appendix 5 Committee representation

Name of committee	Staff member
International committees	
EEC Climate Change Research Committee	P G Whitehead
EEC ENCORE Modelling Group	P G Whitehead (Chairman)
European Geophysical Society Hydrological Sciences Committee	R J Harding
European Network of Experimental & Representative Basins	M Robinson (UK representative)
FRIEND Steering Committee	A Gustard (Chairman)
GEWEX Continental International Programme (GCIP) Science Panel	W B Wilkinson
GEWEX Continental International Programme (GCIP) Science Panel	N W Arnell
IDNDR Working Group on Drought Mitigation	J S Wallace
International Association of Hydrogeologists UK Committee	W B Wilkinson
International Association of Water Pollution Research & Control (IAWPRC), UK Committee	W B Wilkinson
International Committee on Atmosphere-Soil-Vegetation Relations	J S Wallace (UK representative)
International Decade for Natural Disaster Reduction (IDNDR) Drought Working Party	W B Wilkinson (Chairman)
International Decade for Natural Disaster Reduction (IDNDR) UK Coordinating Committee	W B Wilkinson
International Journal of Climatology. Editorial Board	R J Harding
Journal of Agriculture & Forest Meteorology: Editorial Board	J S Wallace
NATO Panel on Science of Global Environmental Change	M A Beran
UNESCO International Hydrological Programme IV Project H 5 5	A Gustard
UNESCO International Hydrological Programme UK Committee	W B Wilkinson (Chairman)
WMO Commission for Hydrology	W B Wilkinson (UK Principal Delegate)
WMO Commission for Hydrology. Advisory working Group	M A Beran
WMO Commission for Hydrology: Working Group on Operational Hydrology, Climate and the Environment	M A Beran (Chairman)
WMO-RA Working Group on Hydrology	M A Beran
National committees	
1994 GEWEX Conference Committee	J B Stewart (Chairman)
British GENIE Data Users Committee	F M Law
British Geomorphological Research Group	P Naden (Hon. Treasurer)
British Hydrological Society Main Committee	C Kirby (IH representative/Editor)
British Hydrological Society Main Committee	F M Law
British Hydrological Society Research Sub Committee	F M Law (Chairman)
British Hydrological Society Southern Section Committee	N W Arnell
BSI Measurement of Fluid Flows Estimation of Uncertainties PCL/2/8	I G Littlewood
BSI Precipitation Measurements PCL/3/ /2	D C Morris
CIRIA Steering Committee - Rising Groundwater Levels - London	W B Wilkinson
CIRIA Steering Committee - Rising Groundwater Levels - Birmingham	W B Wilkinson
DOE Acid Waters Monitoring Group	P G Whitehead
DOE Acid Waters Review Committee	P G Whitehead (Chairman)
DOE Critical Loads and Acid Deposition Group	P G Whitehead
DOE Water Quality Advisory Committee	P G Whitehead
Environmental Physics Group of the Institute of Physics	J B Stewart (Chairman)
GENIE Joint Data Centres Data Users Committee	M A Beran
Geological Remote Sensing Group of the Geological Society	J W Finch (Secretary)
Hazards Forum Natural Hazards Sub-Committee	F M Law (Technical Secretary)
ICE Conference on Groundwater Problems in Urban Areas - Organising Committee	W B Wilkinson (Chairman)
ICE Reservoir Floods Working Party	F M Law
Institution of Environmental Sciences Council	H R Oliver

Interdepartmental Committee for Hydrology	W B Wilkinson (Chairman)
IWEM River and Coastal Panel	F M Law
IWEM Water Resources Panel	T J Marsh
Meetings Committee, Royal Meteorological Society	J B Stewart
NRA Research Fellowships Committee	P G Whitehead
ODA Engineering Research Group	A G P Debney
ODA Remote Sensing Working Group	J W Finch (Chairman)
Southampton University Institute of Irrigation Studies, Advisory Board	H M Gunston
Surface & Groundwater Archives Steering Group	M L Lees
UK GEWEX Forum	M A Beran
University of Reading Postgraduate Research Institute for Sedimentology, Advisory Board	W B Wilkinson

Research Council committees

NERC Airborne Remote Sensing Steering Committee	J W Finch
NERC Arctic Terrestrial Ecology Special Topic Steering Committee	R J Harding
NERC Atmospheric Sciences Committee	W B Wilkinson
NERC Equipment Pool for Field Spectroscopy Steering Committee	J W Finch
NERC/ESRC Land Use Programme Advisory Committee	W B Wilkinson
NERC HYREX Committee	E J Stewart (Secretary)
NERC Information Services Advisory Committee	F M Law
NERC Land Ocean Interaction Study (LOIS) - Steering Committee	W B Wilkinson
NERC Scientific Computing Advisory Committee	P G Whitehead
NERC Terrestrial & Freshwater Sciences Committee	W B Wilkinson
NERC TIGER 3 Working Group	J H C Gash
TFSD Computing Strategy Committee	P G Whitehead
TFSD Programme Area 13 Core Group	A G P Debney (Chairman)
TFSD Programme Area 3 Core Group	M A Beran (Chairman)
TFSD Programme Area 3 Core Group	N W Arnell (Secretary)
TFSD Remote Sensing Strategy Group	J S Wallace
TIGER Steering Committee	M A Beran (Secretary)

Appendix 6 The UK HOMS office

WMO's Hydrological Operational Multipurpose System (HOMS) is a simple but effective technique for technology transfer which has been running successfully for many years. Sponsored and funded centrally from the World Meteorological Organization's headquarters in Geneva, HOMS operates through a network of 110 national hydrological organisations.

The United Kingdom office for HOMS is based at the Institute of Hydrology. Here the latest update of the HOMS manual is used to assist with enquiries, and information packages are distributed on request.

The UK now has 23 components in the international HOMS manual, representing over 5 per cent of the total number available from all countries. We also have five more components currently under consideration for inclusion. Since April 1990 a total of 188 components have been supplied by the UK office, of which 66 were supplied during the calendar year 1992, following a publicity drive. This compares with 224 for the whole of the scheme around the world, i.e. 30% of the annual total was supplied by the UK. A further 29 requests have been met so far in 1993, making the UK HOMS office one of the most active in the world.

Requests come not only from developing countries but also from developed countries for use by consultants for overseas work applications. In March 1993 letters and questionnaires were sent to recent recipients of UK components asking for feedback on the use that had been made of them. Of the 64 responses received, 54 components had been found to be useful or very useful, showing that the UK components are generally really appreciated. Similar surveys will be held in the future, after the most recent components supplied have had time to be tested.

Appendix 7 Links with other organisations

Collaboration with other research organisations

UK Research Organisations

In addition to numerous collaborative research projects with sister Institutes in the Natural Environment Research Council, the Institute of Hydrology is involved in collaborative projects with more than 50 research organisations, a selection of which are listed here.

University of Birmingham
UCNW, Bangor
Cambridge University
Cranfield Institute of Technology
University of Durham
University of East Anglia
Imperial College
University of Manchester
Nuffield College, Oxford
Reading University
Rothamsted Experimental Station
University of Sheffield
Silsoe College
Soil and Water Research Station (ADAS)
University of Wales, College of Cardiff
Hadley Centre for Climate Prediction & Research
Institute of Ecology & Resource Management
Oxford Forestry Institute

International research organisations

IH is currently involved in more than 40 international projects in collaboration with more than 200 research organisations worldwide.

Europe

Universite de Liège, Belgium
Czech Hydrometeorological Institute
National Board of Waters & the Environment, Finland
ORSTOM, Montpellier, France
CEMAGREF, Lyon, France
Institut National de la Recherche Agronomique, France
Universitat Bayreuth, Germany
Institut für Wasserwirtschaft, University of Hannover, Germany
National Technical University of Athens, Greece
Universita de Padua, Italy
Universita degli Studi di Bologna, Italy
Agricultural University, Wageningen, The Netherlands
Norwegian Institute for Water Research (NIVA)
Institute of Meteorology and Water Management, Poland
Universade Tecnica de Lisbōa, Portugal
Direcção de Servicos de Hydrologia, Portugal
State Hydrological Institute, Russia
Universidad Autonoma de Barcelona, Spain
Universidad de Castilla-La Mancha, Spain
Swedish Environmental Research Institute

Africa

ICRISAT Sahelian Centre, Niger
Nigerien National Meteorological Research Centre, Niger
University of Dar es Salaam, Tanzania
Department of Research & Specialist Services - Zimbabwe

Americas

NHRI, Saskatchewan, Canada
Atmospheric Services Unit, Environment Canada
NASA GFDL Greenbelt, Maryland, USA
University of Arizona
US Forestry Service
Technical Institute of Sonora, Mexico
Instituto Nacional de Pesquisas Espaciais, Brazil
Centro de Pesquisa Agroforestal da Amazonia Ocidental, Brazil
CENA, Brazil

Asia & Australasia

Australian National University
National Agricultural Research Centre, Nepal
Karnataka State Forest Department, India
Ministry of Agriculture & Water Development, Sri Lanka

Client Organisations

UK Government

Department of the Environment
Ministry of Agriculture, Fisheries & Food
Overseas Development Administration
Department of Trade & Industry
Welsh & Scottish Offices
National Rivers Authority
Strathclyde River Purification Board
Highland River Purification Board
States of Jersey Public Services
Scottish Natural Heritage

UK Private Sector

National Power plc
National Grid
Powergen
Severn Trent plc
Welsh Water plc
Binnies & Partners
HR Wallingford Ltd
Ove Arup & Partners
Posford Duvivier Ltd
Sir Alexander Gibb & Partners
Southern Science Ltd
Hydrotechnica Ltd
ICI
Logica
Servelec
National Remote Sensing Centre Ltd
Amey Roadstone Ltd
British Aerospace
British Airports Authority
Crouch Hogg Waterman
ENSIS Ltd
Roffe Kennard & Lapworth Ltd
United Distilleries

International

The Institute of Hydrology has been commissioned to undertake hydrological studies in more than 65 countries, for governments, international agencies and private sector clients. Projects were undertaken during 1992/93 for the following organisations:

Commission of the European Communities, DG's I, XI, XII
World Meteorological Organization

United Nations Development Programme
UN Food and Agriculture Organization
UNESCO
World Bank
Government of Lesotho
Government of Botswana
Government of Qatar
Government of Hong Kong
Arab Potash Company
Sonel/Lahmeyer
Mysore Paper Mills Ltd
Philippines Atmospheric, Geophysical & Astronomical Services

Appendix 8 Training and education

In addition to applied research for private sector clients, the Institute of Hydrology also has an active programme of Technology Transfer and Training. Research results are disseminated through a wide range of publications, software packages and training courses.

Courses

In the year to March 31st 1993, the following courses were given by Institute of Hydrology staff in collaboration with the facilities provided by Water Training International at Tadley and Kilwinning.

ER2 (1 week)
  Advanced Flood Estimation;
  The Flood Studies Report
ER6 (week)
  Basic Flood Estimation;
  Flood Estimation for Small Catchments
SP348 (1 week)
  Low River Flows

IH staff contributed to other short courses:

River Pollution, and Flood Mitigation
  Dept of Civil Engineering, University of Bristol

Weather Radar & Flood Forecasting
  University of Padua, Italy

Workshop on Rainfall Estimation and Forecasting using Weather Radar
  National Technical University of Athens, Greece

Software training

7-11 April 1992
HYDATA workshop, Institute for Meteorological Training and Research, Nairobi (funded by WMO & ODA)
8 July 1992
HYDATA training within the CHICOM course at Reading University
20-21 July 1992
QUASAR workshop, for South West Water
29 January 1993
Seminars on IH software packages given at the software Open Day at IH
22-27 March 1993
HYDATA workshop, Institute for Meteorological Training and Research, Nairobi (funded by WMO and ODA).

Training given to university students

Institute staff co-supervised postgraduate students working for doctorates at the universities of Salford and Reading:

J. Butterworth (working in Zimbabwe)
S Gaze (working on the SAGRE programme in Niger)
A. Wild (hydrometeorological inputs to the Irish Sea)

In addition several postgraduate CASE students are registered with the institute

M. Albequerque, BSc – Soil Science Dept., Reading University
L. Bull, BSc - Birmingham University
A. L. Collins, BSc - Exeter University
S. Evans, BSc – University of Nottingham
J. Fisher, BSc – Lancaster University
N Harris, BSc – Birmingham University
S Henworth, MSc – Southampton University
K J. Neylon BSc – Reading University
D A. Post, BSc – Lancaster University
A. Wild, BSc – Salford University
C Williamson, BSc - St Andrews University
M. J. Varley, BSc – Lancaster University
J. S J Worrall, BSc – Institute of Sedimentology, Reading University

MSc students were hosted from the universities of Birmingham Bournemouth Delft and University College, London

Two months industrial experience and research training was given to a mathematics student from Bristol University (under the NERC competitive grant scheme for maths or physics students)

Several staff act as PhD external examiners at the universities of London, Reading and East Anglia.

Liaison with schools

The Institute participates in the national School Work Experience Scheme and five students from local schools worked at IH for one or two periods during the year IH staff also attended school-employer link meetings and other career-oriented occasions at local schools.

Appendix 9 Visitors

Since water is central to so many human activities, there are many players benefiting from hydrological R & D. These are spread throughout Government, public and private services, agriculture, industry, environment and academia. Over and above regular meetings which take place with other researchers and our customers, the work of the Institute continually attracts many visitors with wide interests in water across business, academic and planning issues from throughout the UK, the European Community and from many other overseas countries.

The Institute, together with the British Geological Survey Hydrogeological Group, presented *Water Sciences at Wallingford* to the UK water industry on 1st October 1992. Representatives attended from the recently formed Water PLCs, other Water Companies, The Scottish Office, Water Services DoE(NI), Scottish Regional Councils and British Water Associations. Demonstrations and seminars presented work related to water resources and water quality issues, asset management, information support systems for operational water management and the National Surface and Groundwater Archives at Wallingford.

A second Open Day in January 1993 allowed some 100 visitors to see demonstrations of scientific software and, through seminars and workshops, to examine applications and the underlying science across a range of products designed to place IH know-how in the hands of practitioners. Visitors were from many of the major UK environmental consultants and consulting engineering firms, National Rivers Authority regional offices, Scottish River Purification Boards, Local Authorities, Water PLCs, several HEIs using IH software for teaching, and from other UK research institutes with interests in scientific software as a route for technology transfer.

The Institute regularly hosts visits explaining the role of NERC and research in hydrology to organised parties. During the year we were delighted to welcome 20 students from the Water Resources Technology and Management MSc Course, University of Birmingham and a party of 30 students and lecturers from the Wageningen Agricultural University postgraduate Soil Water and Atmosphere course. During September 1992 we entertained a party of 15 Czechoslovakian experts from Water Boards, Meteorological and Water Research Institutes and the Ministry of Environment as part of a familiarisation tour of the UK water industry. Closer to home the Chairman and Members of the South Oxfordshire District Council, our neighbours at Wallingford, visited to learn more about the organisation of environmental research in the UK and the work of IH in support of the UK water industry.

In June 1992 the Rt. Hon. Michael Howard (then Secretary of State for the Environment) visited IH scientists at the field site north of Manaus where the joint Anglo-Brazilian ABRACOS project is investigating climatic effects of Amazonian deforestation.

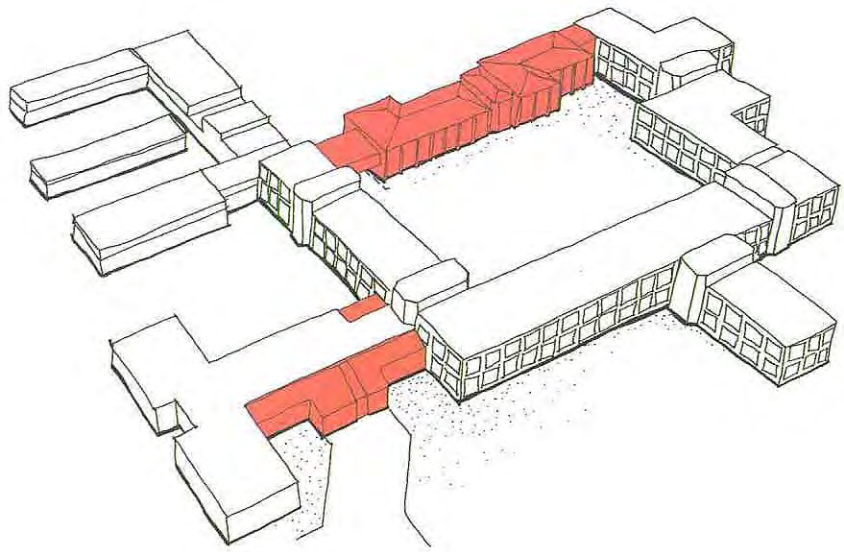
Bi-lateral collaboration and study tours funded by the British Council provided opportunities for many overseas visitors to spend periods ranging from a day to several weeks at the Institute. Visitors from Hungary, Chile, France, Russia, Japan, Italy, Holland, Poland, Germany, Kenya and Brazil were received during 1992/93.

Appendix 10 Proposed extension to the Wallingford site

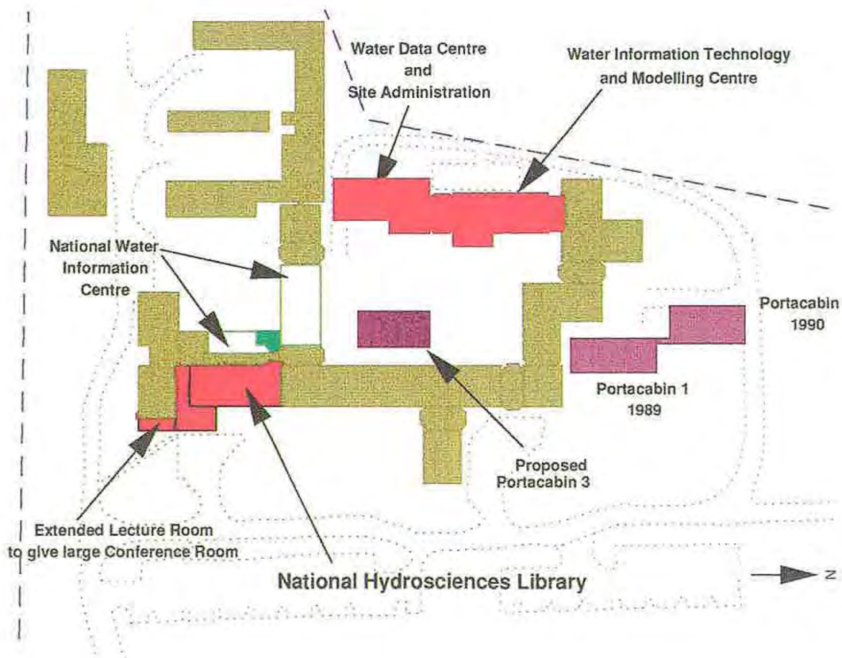
The Institute of Hydrology is based at the NERC Wallingford Laboratory together with a field research centre in Wales at Plynlimon and an office in Scotland at the Stirling Science Park. The Wallingford Laboratory was built in 1972 to house an IH staff of 96. Extensions were added in 1978 and 1980 to accommodate the Hydrogeology Group of the NERC British Geological Survey and in 1985, units of the NERC Computer Services group transferred to Wallingford.

In 1992-93 the Wallingford Laboratory accommodated 164 IH staff, 50 BGS and 20 NCS personnel and about 40 visiting scientists, students, contractors and casual staff. Accommodation is provided in the main building and two temporary Portakabins whilst a third is planned to alleviate continuing pressures on experimental facilities and provide space for networked computing arrangements.

Following the 1991 Science Management Audit of IH, the Director was asked to prepare proposals for a permanent solution to the accommodation difficulties at Wallingford. A range of building extension options have been explored and submitted to NERC. These centre around consolidation of the extensive environmental data functions of the Institute of Hydrology and the Hydrogeology Group of BGS at Wallingford. A National Hydrosciences Library and National Water Information Centre are proposed to facilitate greater public and professional access to the work and water data holdings at Wallingford.



Architect's impression of Option 4



Appendix 11 Abbreviations and acronyms

ABRACOS	Anglo-Brazilian Amazonian Climate Observational Study
ADAS	Agricultural Development and Advisory Service (MAFF)
BOD	Biological Oxygen Demand
BOREAS	Boreal Ecosystems — Atmosphere Study
CLIMEX	Climate change Experiment
DOE	Department of the Environment
EFEDA	European Field Experiment for Desertification-threatened Areas
FRIEND	Flow Regimes from International Experimental and Network Data
GCIP	GEWEX Continental-Scale International Project
GCM	General Circulation Model
GEV	Generalised Extreme Value
GEWEX	Global Energy and Water Experiment
GIS	Geographical Information System
HAPEX	Hydrosphere Atmosphere Potential Evaporation Experiment
HRI	Horticulture Research International
HYREX	Hydrological Radar Experiment
IDNDR	International Decade for Natural Disaster Reduction
IGBP	International Geosphere Biosphere Programme
IHACRES	Identification of unit Hydrographs And Components from Rainfall Evapotranspiration and Streamflow data
IUCN	International Union for the Conservation of Nature and Natural Resources
LCPD	Large Combustion Plant Directive
LOIS	Land Ocean Interaction Study
LRTAP	Long Range Transboundary Air Pollution
MAGIC	Model of Acidification of Groundwater in Catchments
MITRE	Met. Office IH Terrestrial model
MORECS	Met. Office Rainfall and Evaporation Calculation System
NRA	National Rivers Authority
SLIM	Soil Leaching Intermediate Model
SSLRC	Soil Survey and Land Use Research Centre
SVAT(S)	Soil Vegetation Atmosphere Transfer (Scheme)
TIGER	Terrestrial Initiative in Global Environmental Research
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational Scientific and Cultural Organization
WCP	World Climate Programme

Appendix 12 Wallingford meteorological station: 1992 summary

The meteorological station maintained by the Institute of Hydrology has been in operation since 1962. Located at National Grid Reference SU 618 898 at an altitude of 48 m above Ordnance Datum it is recognised as a voluntary climatological station reporting to the UK Meteorological Office; observations are taken at 9 a.m. GMT both weekdays and weekends. Contemporary and long-term data from the site are used in hydrological monitoring programmes and to support a range of research activities. As a Thames Valley floor site over gravels, the temperature readings include regionally notable grass minima.

1992 meteorological review

Despite below average sunshine hours, temperatures were appreciably above the 29-year mean continuing a sequence of warm years beginning with 1988. Rainfall conditions showed a remarkable contrast through the year. January and February were notably dry and culminated in the second driest August-February sequence on record. More remarkably, the two-year period from March 1990 is the driest 24-month sequence, for any start month, on record; the accumulated rainfall total for the four years ending in February 1992 is also unprecedented. Subsequently the drought eased and from early March rain was registered on around half the days through until December. Long-term rainfall deficiencies were substantially reduced over the latter half of the year. The five-month sequence beginning in July was the second wettest on record, reflecting (in part) a vigorous thunderstorm on 22nd September which produced a precipitation total of 58 mm. This is the fourth highest daily rainfall total in the 30-year series and provided a notable marker in the transformation from severe drought conditions to the moderate local flooding which characterised the late autumn and early winter.

Month	Mean air temperature °C				Total rainfall mm			Days with rain	Total sunshine hours		
	1992	lta*	max	min	1992	lta*	%*		1992	29y*	%*
Jan	3.2	3.5	6.7	0.6	19.0	50.5	38	7	39.1	47.8	82
Feb	4.8	3.4	7.2	0.3	17.6	33.4	53	10	55.8	66.5	84
Mar	7.7	6.0	9.9	1.9	41.4	44.5	93	19	55.4	103.8	53
Apr	8.9	8.2	12.6	3.1	54.3	40.8	133	16	57.4	145.3	40
May	14.5	12.0	16.4	6.2	62.4	49.7	126	10	253.2	183.4	138
Jun	16.4	15.1	19.5	8.9	39.9	51.6	77	7	209.7	186.4	112.5
July	17.2	17.4	21.7	10.9	63.6	43.9	145	15	147.0	185.6	79
Aug	16.8	16.9	21.3	10.8	98.9	55.6	178	20	139.9	175.3	80
Sep	14.2	14.0	18.6	8.9	92.5	50.3	184	16	114.5	137.9	83
Oct	8.1	10.2	14.7	6.4	66.0	51.5	128	14	89.4	97.6	92
Nov	7.9	6.4	10.0	3.0	105.6	54.3	194	22	57.3	62.6	92
Dec	3.3	4.7	7.7	1.4	54.4	55.9	97	14	48.5	38.2	127
YEAR	10.2	9.8	13.9	5.2	715.6	582.0	123	170	1267.2	1430.4	89

* lta is the long-term average (based on 1962-1991 data);
29y is the 29-year monthly mean;
% is the 1992 figure as a percentage of lta or 29y.

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Natural Environment Research Council

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