1991 — 1992
REPORT

Institute of Hydrology

Natural Environment Research Council

Foreword

The year covered by this report has proved both challenging and fruitful for the Terrestrial and Freshwater Sciences Directorate (TFSD). Implementation of NERC's strategy for the terrestrial and freshwater sciences (the Green Light, published in March 1989) is providing a focus for our research in the areas of land use, the maintenance of environmental quality, and the principles which underlie environmental management and conservation. Initiatives started in previous years, in particular the Terrestrial Initiative in Global Environmental Research (TIGER), are now well under way. The Environmental Change Network and the Land Ocean Interaction Study are now moving forward as developing programmes, and new ideas are in the planning stage. Increasingly, programmes have been established jointly with other Research Councils so that a much broader approach to scientific problems is possible, and with larger funding.

The Directorate's expertise in 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, London), the Unit of Behavioural Ecology (Oxford University) and the Unit of Comparative Plant Ecology (Sheffield University) provides an unrivalled, interdisciplinary research base with international reputation.

This is the last year in which I shall be writing the Foreword to the Directorate's annual reports. It has been a pleasure to have been associated with IH which is recognised internationally as being in the forefront of hydrological research. As can be seen from this report, the research in tropical forestry in Brazil, drylands in the Sahel and the Global Energy and Water Experiment (GEWEX) are all providing answers to important issues at the global scale. Within the UK and Europe, its expertise on managing and predicting hydrological processes is outstanding, and in great demand.

Dr P B Tinker
Director of Terrestrial and Freshwater Sciences
Natural Environment Research Council

Front cover illustration:
Waterfall below Eagle Rock, Monachyle, Perthshire
Photograph: J R Blackie, IH

Report of the Institute of Hydrology 1991/1992

Natural Environment Research Council

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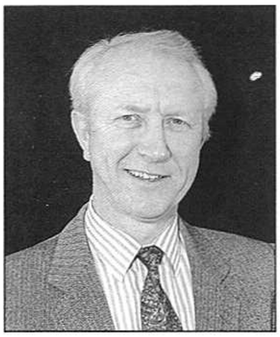
Director's Introduction



Professor Brian Wilkinson

This year's report follows the format adopted for the first time last year. Nine major hydrological themes have been selected and the Institute's progress and achievements within each one described.

The Institute has had a most successful year. The number of external publications and commissioned research reports has increased; new software packages have been prepared and world wide sales are buoyant; staff and student numbers have grown from 152 to 167, and the value of research contracts showed an increase of over £0.5 million as compared with last year — a rise of 13 per cent.

This continued growth in activity and the vibrant nature of our research programme owe much to the scientific skills, enthusiasm and hard work of the staff. However, there are also other factors operating, principally the recognition, growing steadily over the last decade within the scientific community, UN agencies, national governments and regulating agencies, of the key role that hydrology plays in a wide range of development and environment issues. These include the protection of communities against natural hazards, the design and operation of water resource systems, and alleviation or control of water pollution. The overall aim of hydrological research is, of course, to provide a better understanding of all environmental problems at local, regional and global scales.

Some of the above issues were addressed in depth at the International Conference on Water and the Environment (ICWE) held in Dublin, Ireland, in January 1992. With 114 countries, 38 non-governmental organisations, 14 inter-governmental organisations and 28 UN bodies and agencies participating, ICWE was without doubt the most significant global conference on water since the United Nations Water Conference held in Mar del Plata, Argentina, in 1977. This Institute worked closely with UK government departments and the National Rivers Authority in the preparation and publication of the British Statement "*Water and the Environment*" which was presented at Dublin.

The "Dublin Statement" which emerged from the meeting noted that "Scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. Human health and welfare, food security, industrial development and the ecosystems on which they depend, are all at risk, unless water and land resources are managed more effectively in the present decade and beyond than they have been in the past". This Statement provided the major input on freshwater problems to the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in June 1992.

In the previous annual report I described in some detail the Institute's input to international science programmes such as the International Geosphere Biosphere Programme, the World Climate Programme, the International Decade for Natural Disaster Reduction, and the International Hydrological Programme. This has been further strengthened during the past year. Our research on water and energy balance at the land surface/atmosphere interface, which covers a range of environments from the tropical forests of Amazonia to eucalyptus plantations in India to the semi-arid lands of Africa, has made excellent progress during the year, achievements which are described later in this report.

A new initiative was developed between the Institute and the Royal Geographical Society to study Water Erosion and Land Management in Nepal: the project which is being undertaken with the full collaboration of the Central Division of Soil Science, His Majesty's Government, Nepal, was launched in July 1991 by Sir Crispin Tickell (President, RGS) and myself. The sustainable use of land, water and agricultural resources is essential to the development of Nepal. Loss of topsoil, silt infilling of reservoirs, damage to irrigation canals, increased flooding and deterioration in water quality are some of the pressing problems that the research will address. The three-year project is being funded by the Overseas Development Administration (ODA) with contributions from Land Rover.

So far I have focused on the Institute's international research activities but research achievements at home are no less noteworthy. We have, for example, completed major reports for the Department of the Environment and the National Rivers Authority on the impact of climate change in the UK. Research on mathematical models developed for flood forecasting for Yorkshire are complete and the scheme is shortly to become operational.

Our work on the management of complex water resource systems in the Thames Basin during drought was completed before the start of the year under review but it is gratifying to report that the quality of the science was recognised by the International Association of Hydrological Science

(IAHS) when R J Moore received the Tison Award for his publication on this topic in their journal with fellow authors D A Jones and K Black

Joint research with the University of Sheffield has led to the development of new statistical techniques to analyse the spatial and temporal distribution of rainfall within the UK The Institute's own Geographic Information System, the Water Information System (WIS) which can hold and manipulate both spatial and time series data, is receiving much attention from both the UK Water industry and other non-water organisations Indeed, these two projects are good examples of the generic nature of much of our research, i.e. the techniques we have developed to support specific hydrological research aims have application over a much broader science span. We have also continued to expand our more applied hydrological analyses and software packages to support the environmental and engineering consultancy firms within the UK. Through this route Institute science is contributing directly to wealth generation.

Two Community Science programmes have recently been established by the Institute's parent body, the Natural Environmental Research Council. The first is the Terrestrial Initiative in Global Environmental Research (TIGER). This four-year programme began in 1991 and has as its principal objective research on the carbon cycle on land, trace greenhouse gases, water and energy balance and impacts on ecosystems, all with the overall aim of creating a better understanding of the processed in the biosphere so that causes and consequences of climate change can be foreseen and forestalled. The Institute has bid successfully for several major research projects within TIGER.

The second programme is LOIS (Land Ocean Interactive System) running for five years from April 1992. The Institute helped draft the Science Plan for LOIS and will be establishing many of the land-based monitoring networks and databases. as well as bidding for specific projects within the programme. The research will focus on the coastal zone between the Humber and the Tweed estuaries and the catchments draining to it, drawing together for the first time terrestrial. freshwater, marine and atmospheric scientists from all over the UK.

The current strength of the Institute owes much to the relevance of our research to resource development and environmental issues. Another factor, however, is the strength of the foundation on which the Institute science has been built over the years It is interesting to look back 20 years to the Institute's report for 1971-72 when the focus was mainly on UK catchment experimentation and how it fitted into the international programmes of the time such as the International Hydrological Decade. The Chairman of the Institute's Advisory Board was Dr H L Penman and in his foreword he refers to the newly established catchment experiments at Plynlimon and elsewhere. Penman's text reflects the excitement of "...turning a remote rain-drenched mountain side into an open air laboratory..." The then Director — Dr Jim McCulloch — in his introduction cautioned against under-valuing hydrology as an applied science because "... it has been practised before the scientific principles have been fully appreciated,. The establishing of hydrology as a science as well as a practice has necessitated fundamental studies of the behaviour of water in its many phases in the hydrological cycle This involves research " During the subsequent years the Director pressed forward with this philosophy and built the strong science foundation on which the Institute stands today Jim McCulloch, I salute your scientific vision.

Finally, it is my hope that from this introduction and the main body of the report, an important message is conveyed of an Institute which:

- has a well-founded programme of hydrological research that is addressing both UK and global issues,
- is working with other nations to share scientific findings and the costs of international programme;
- has — and continues to develop — scientific techniques that are valuable, not only to the hydrological sciences. but have wider applications, i.e. they are generic in nature:
- has made significant advances with its scientific achievements over the past year and
- is contributing through its research to wealth creation.

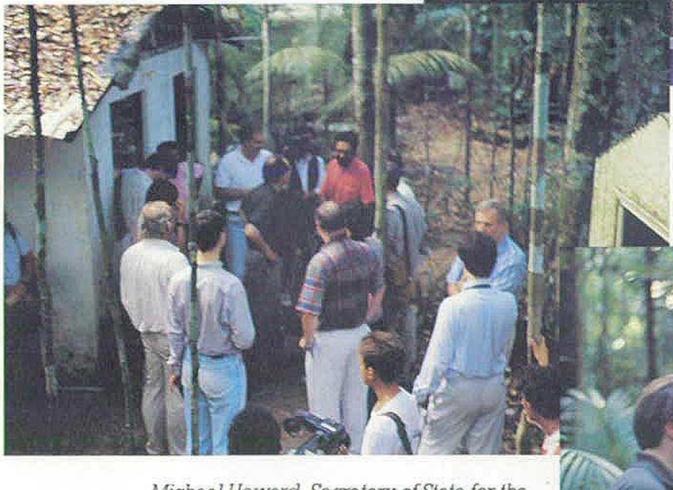
Brian Wilkinson

Visitors

Perhaps because of the increased awareness of how water problems impinge on daily lives, the Institute has been favoured with no fewer than three Ministerial visits this year. On the first two occasions we were delighted to host visits at Wallingford from Mr Alan Howarth, Parliamentary Under Secretary for Education and Science, and from Mr David Trippier, Minister of the Environment and Countryside. The third visit, that of the Rt Hon Michael Howard, Secretary of State for the Environment, took place in conjunction with the high profile Earth Summit at Rio de Janeiro.

Science Minister Alan Howarth (left) with Brian Wilkinson, Director of IH, during the Minister's visit to Wallingford on 11 July 1991. On completion of his visit, Mr Howarth said: "I have been very impressed by the quality and depth of research I have seen here today. The Institute is clearly a centre of excellence as far as water engineering is concerned and I congratulate the staff on the valuable contribution they are making to worldwide knowledge and understanding."

David Trippier, Minister of the Environment and Countryside (centre) hearing about some of the Institute's research in the Amazon rainforest from Jim Shuttleworth (Head of Processes Division) during his visit to IH on 19 December 1991 to see some of the research funded by his Department.



Michael Howard, Secretary of State for the Environment, surrounded by media people during his visit in June 1992 to the joint Anglo-Brazilian field site north of Manaus. The ABRACOS project (see page 13) aims to improve predictions of the climatic effects of Amazonian deforestation.

National hydrological monitoring: the NW/SE rainfall gradient steepens

The climate of the UK is noted for its short-term variability: sustained sequences of either very wet or very dry weather are relatively rare. Human, animal and plant communities adjust, often over lengthy periods, to the climate's capricious nature. Only when the normal range of variation is exceeded do the stresses on man and the environment, caused by too little or too much rainfall, become clearly evident.

The vulnerability of the UK to unusual weather patterns has been heavily underlined over the last four years. A very protracted drought has afflicted much of eastern and southern England whilst northern Scotland has been very wet and had to cope with a number of notable flood events. The possibility that such conditions may recur with greater frequency in the future has focused attention on the need to strengthen the scientific foundation upon which the formulation of environmental policy and the development of water management strategies are based (see Figure 1).

In large part the creation, early in 1992, of the National Water Archive (NWA) represents a response to this need. The NWA is the most recently established of NERC's Designated Data Centres. However, the Wallingford site has long been a natural focus for the acquisition and exploitation of major hydrological databases. For more than a decade stewardship of the national river flow and groundwater level archives has rested with IH and the British Geological Survey respectively. These databases form the kernel of the National Water Archive, but a very broad range of hydrological, and related, data sets are being assimilated into the coordinated management that the NWA provides.

Information stored in the Archive provides the necessary historical perspective within which to examine the recent extraordinary spatial and temporal variations in rainfall, river flows and aquifer replenishment. Monthly Hydrological Summaries for Great Britain and other authoritative documentation of the recent floods and the prolonged lowland drought has been furnished by a joint IH/BGS hydrological monitoring programme. A range of associated briefing material has been widely used to index drought severity, to increase public awareness of hydrological issues and to help identify research opportunities.

The River Ver in Hertfordshire, a typical victim of the prolonged drought in south-east Britain in 1991

Recent rainfall patterns over Great Britain

Ironically, rainfall for the whole of Great Britain over the four years beginning in the spring of 1988 was very close to the long-term average. For much of that time, however, many rain-bearing systems followed a relatively northerly track remote from the English lowlands. Additionally, thunderstorms which usually contribute a significant proportion of the summer rainfall in eastern England were relatively infrequent over the period 1989-91.

Consequently, the normal north-west to south-east rainfall gradient across Great Britain was strongly accentuated. Rainfall over the Scottish Highlands was around 120% of average rainfall whereas, over the four years, many districts in East Anglia and the Thames Valley received less than 80%. The north-eastern seaboard was also very dry. Historical rainfall records suggest that such persistent anomalies may be expected, on average, less than once every 50 years. Winter precipitation in Scotland was exceptional. Heavy rainfall on saturated catchments, combined sometimes with a snowmelt contribution, produced major — and widespread — flood events early in both 1989 and 1990. These resulted in extensive transport disruption and damage to very large tracts of agricultural land. A very wet phase in western Scotland was concluded in 1990: runoff from many Highland rivers over the period 1983-1990 was 20-30% greater than the average for the preceding record.

In terms of overall impact, however, the limited rainfall in southern and eastern Britain was of greater significance. The regions of maximum drought intensity broadly coincided with the English lowlands where concentrations of population, commercial activity and intensive agriculture generate the highest demand for water and impose the greatest threat to the aquatic environment. In parts of eastern England the drought can be traced back to early 1988 but a couple of short wet interludes, most notably the December 1989 - February 1990 period, partitioned the lowland drought into separate phases. The drought's greatest severity was achieved over the period beginning in March 1990. Rainfall for England and Wales over the ensuing two years was the lowest (for any 24-month period) since the 1850s and in parts of East Anglia both 1990 and 1991 rank among the three driest years this century.

The impact on river flows

Notable as the long-term regional rainfall deficiencies are, they fail to convey the full severity of the drought in water resources and environmental terms. Even in an average year potential evaporation losses closely approach rainfall totals over much of the English lowlands. The 1988-91 period is the warmest four-year sequence in a temperature series for central England stretching back over 330 years. Sunshine hours have also been exceptionally high throughout much of the drought.

As a consequence, evaporation losses were unprecedented over wide areas: in 1989 and 1990 potential evaporation rates in southern Britain were more typical of central France. One result in the lowlands has been persistently dry soil conditions extending well beyond the summer. The parched soils have robbed the limited rainfall of much of its effectiveness in sustaining river flows and replenishing reservoirs and, especially, groundwater stocks. In broad terms, and considering the full compass of the drought, a 20-25% shortage of rainfall has been translated into a reduction of more than 50% in runoff and aquifer recharge rates.

Some eastern rivers remained at below-average monthly flows for well over three years. Since the late-spring of 1990, monthly runoff totals remained close to the long-term minimum for long periods. The depressed nature of river flows is perhaps best exemplified by the River Lee in Hertfordshire (Figure 2). Mean flows for each of the 1991/92 winter months (December-February) at the Feildes Weir gauging station were the lowest in a 109-year record and the runoff over the winter half-year (October-March) — around 25% of the long-term average — is also unprecedented.

The hydrological severity of the drought emerges most clearly when long term runoff accumulations are examined. For the two-year period beginning in July 1990 runoff totals are below any previous 24-month accumulations for many lowland (and some other) rivers. Most UK gauging station records are less than 40 years in length and the low flow statistics for many rivers in eastern, central and southern England have been largely redefined since 1988.

Depressed runoff rates over an extended period have been associated with a shrinkage in river headwaters which is without modern parallel; the loss, albeit temporary, of amenity and aquatic habitat has been considerable. Such problems have been exacerbated in catchments where groundwater pumping, often over many years, has steadily reduced river flows and caused the perennial stream source to migrate downstream. Rehabilitation programmes are now well advanced in some catchments. For example, given sufficient rainfall, the cessation of pumping from a major supply borehole in the headwaters of the River Ver in Hertfordshire is expected to allow groundwater levels to rise and thus produce a healthy aquatic environment in reaches which have been dry for many years.

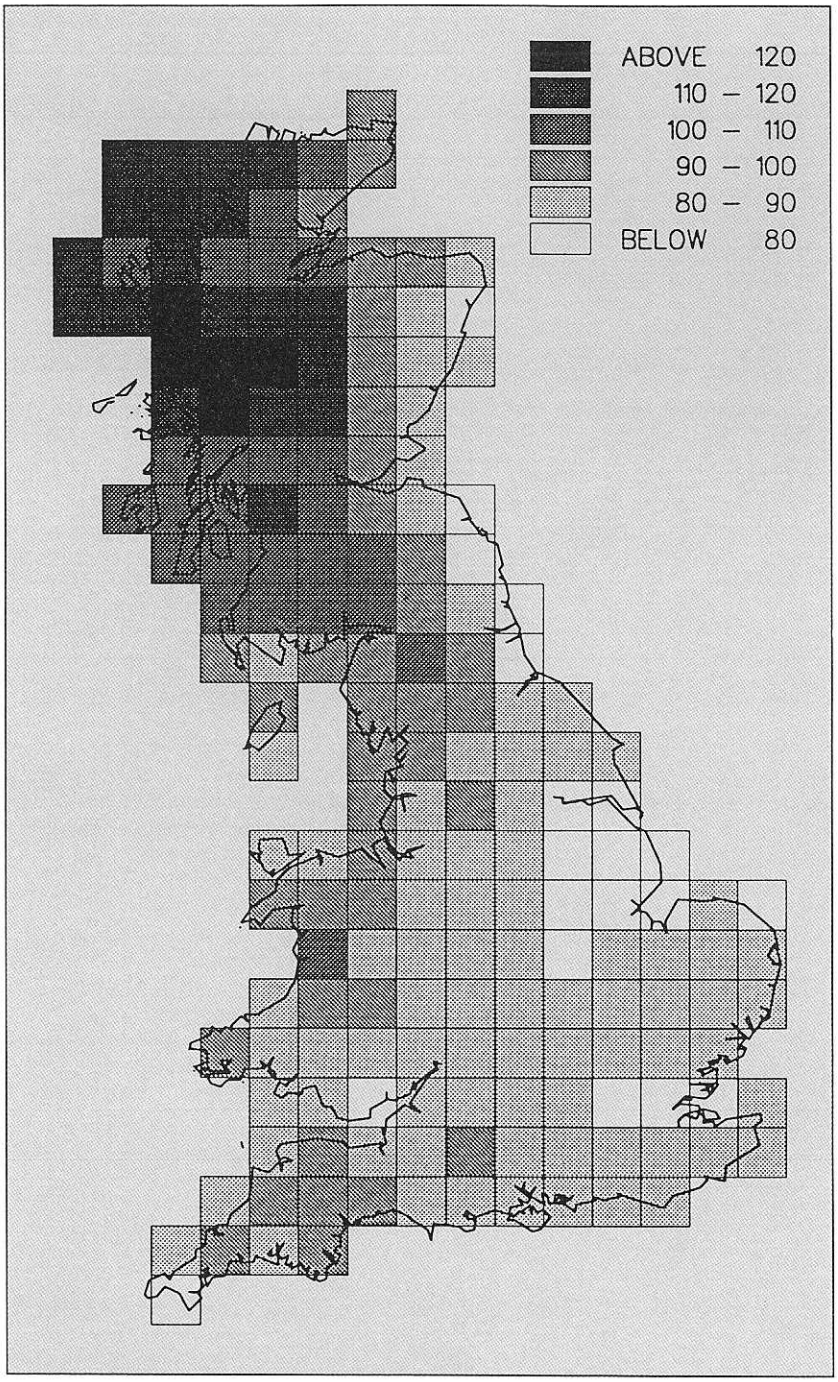


Figure 1 Rainfall for the period August 1988 to February 1992 as a percentage of the 1961-1990 average

The impact on aquifers

Over large areas, four successive winters with modest recharge separated by extended groundwater recessions, provide the background to the very depressed water-tables in 1991/92. The impact on groundwater replenishment is evident from Figure 2 which shows a dramatic decline in groundwater levels at the Washpit Farm borehole in Norfolk since the spring of 1988: over this period total replenishment was only around half that for the previous minimum four-year sequence in a 40-year record. From Humberside to the eastern Chilterns — and probably over a more extensive area — there is no close precedent this century for the inordinately low accumulated recharge over the last four winters. This had

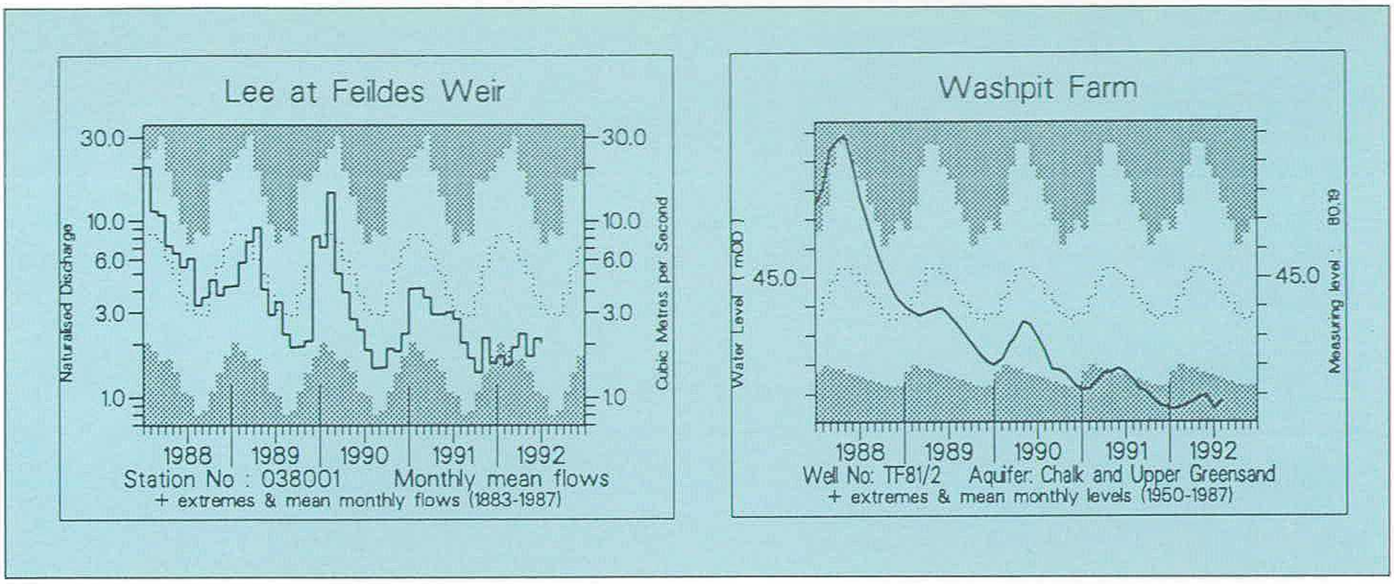


Figure 2 River flows and groundwater levels 1988-92

particularly serious implications for the Chalk aquifer — the major water supply source in the south-east.

Evidence of the singular character of the present drought is provided by 1992 groundwater levels at a number of long-term observation boreholes. At Dalton Holme in the Chalk of the Yorkshire Wolds, early spring levels were the lowest in a series from 1889 and, near the southern boundary of the zone of maximum groundwater depletion, the Therfield Rectory observation borehole (Hertfordshire) dried up in January — for the first time in 70 years. Throughout much of the eastern Chalk, the 1992 spring peak was the lowest on record. Water-tables in some areas declined appreciably below previous minima: this is especially true where groundwater abstraction has produced a local or regional drawdown in levels. Groundwater stocks generally improved in a westerly direction but water-tables remained very low in the sandstones of the midlands and south-west. In the most severely affected areas, water-tables in early 1992 stood below the mean spring level by the equivalent of around twice the average annual recovery.

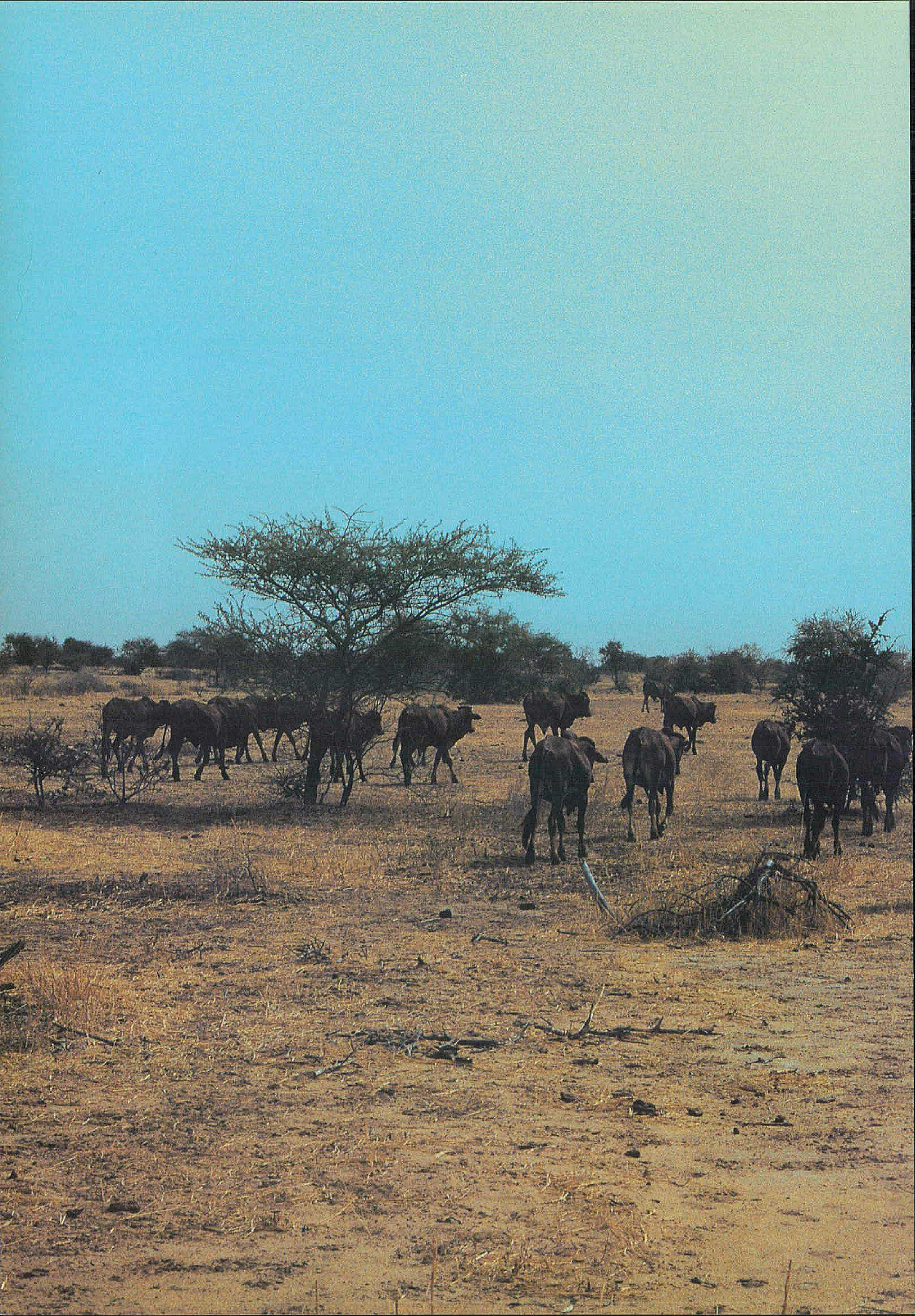
Groundwater resources remained in a very fragile condition through out most of 1991/92. The impact on well yields of the fall of levels into uncharted territory is difficult to predict. Those dwellings and small-holdings dependent for water supplies on shallow wells are particularly vulnerable. There have already been instances in late 1991 and in 1992 of well failures; the expectation must be for substantially more. An exceptionally wet winter (as occurred, for instance, in 1976/77) is required to help return groundwater levels in much of eastern and southern England to within their normal range by the spring of 1993.

Historical perspective

Data from some of our longest established raingauges indicate that the 1988-92 rainfall deficiency, whilst close to the extreme range of normal variability, is not entirely without precedent; four or five broadly comparable episodes may be identified over the last 250 years. River flow and groundwater level records are generally much shorter and, partly as a consequence, may appear to exaggerate the drought's severity. However, temperature data allied to hydrometric information extending back well over 100 years support the contention that the 1988-92 drought is, in hydrological terms, unique in character: the recent paucity of aquifer recharge in large parts of the lowlands has no parallel since the turn of the century.

Direct comparisons between British droughts are hampered by the distinct character of each major period of rainfall deficiency. One common thread throughout has been the increasing influence of the pattern of water use in determining the impact of the drought on the community. The broad coincidence between the regions of maximum drought intensity and the greatest increases in water demand has important implications for the future development of water resources.

Equally significant is a fuller recognition that rising water demand, coupled with protracted shortages of rainfall, poses a real threat to the aquatic environment. The role of groundwater in sustaining lowland rivers and wetland ecology is now receiving much greater attention. With mid-1992 groundwater levels the lowest this century over wide areas, attention is being directed to the development of water management procedures which are better able to reconcile the needs of human and wildlife communities.



Dryland sustainability: a question of balance

Drylands cover over one-third of the earth's land surface, with a human population of some 900 million people. In 25 years' time, the same area will have to provide twice as many people with food, fuel and shelter. The production of plant material — necessary for eating, cooking, building and fuel — is determined principally by the availability of water, a very precious resource in dryland areas. However, there are many examples of inefficient water use: in traditional dryland agriculture less than half the rainfall is used directly in plant production, the rest runs off or is evaporated from the soil surface. As population increases, the consequences of mismanaging the limited natural resources is manifest as an alarming increase in land degradation, currently affecting over a thousand million hectares.

Although the causes of dryland degradation — such as overstocking, deforestation and cultivation of marginal areas — have been known for many years, a major inhibition to progress in combating the degradation process has been a poor understanding of its effect on hydrology. A particular concern is whether land degradation is reversible or whether it permanently alters the hydrology and climate of semi-arid areas.

The Institute has long recognised this need: it has developed research projects specifically designed to address the problem. Land degradation occurs throughout semi-arid areas: in traditional agricultural systems and their associated fallows, and in the adjacent dryland forests which are used for wood and fodder. The Institute's approach has been to build up a number of studies of water balance processes in each of these land-use types.

As the demand for food increases, over-cultivation can occur in traditionally good arable land; the fallow period is reduced or even abandoned. The knock-on effect is the clearance of the adjacent, more marginal, land which supports natural vegetation. This land is often not suitable for sustained cropping. Sustainable cropping practices for any given area are determined by the limitations imposed by water and nutrients, yet systematic data on the water-use efficiency of dryland crops are still rare.

Studies of millet crops by IH in collaboration with the International Crops Research Institute for the Semi-Arid Tropics Sahelian Center in Niger have shown that there is potential for increased productivity. Traditional systems often use less than half of the rainfall for plant growth: the remainder is lost as runoff or direct soil evaporation. The challenge that has faced agronomists for many years is to find new crop management practices which would 're-route' some of this water through the plants to improve their yield within the given climate.

Dryland degradation: cattle walking over dry pastures in the Sahel region of Africa

Another means of increasing crop production, and of introducing diversity in the produce grown, is irrigation. Large-scale irrigation systems have often failed in dryland areas. An alternative is small-scale 'garden' irrigation schemes as an adjunct to traditional rain-fed agriculture. Clearly these resources must be used with optimum efficiency and the total abstraction must not exceed the average recharge if the systems are to be sustainable.

The Institute's research programme in Zimbabwe, funded by the ODA, is addressing these issues in collaboration with the Lowveld Research Station and the British Geological Survey. The main objective is to demonstrate that the sustainability of agriculture in semi-arid areas can be improved by using water from collector wells to irrigate small communal or allotment-type gardens. These irrigation schemes integrate well with traditional farming systems and reduce the reliance of subsistence or semi-subsistence agricultural practices which lead to land degradation, particularly when used intens-ively. Communal irrigated gardens also improve nutrition by providing a range of vegetables in the years when rain-fed farming is feasible.

In drought years, when rain-fed farming is not possible, these irrigated gardens provide the only source of food and, in many cases, income. In contrast to larger irrigation projects, the schemes being evaluated as part of this project are controlled, owned and partly initiated by the farmers themselves. They use a level of technology that can be maintained by the farmers (i.e. hand pumps instead of motor-driven pumps).

The 1991-92 drought in southern Africa had a catastrophic effect on agriculture and the environment. In most of the region there has been no rainfed farming at all during the last year; irrigation schemes using surface or reservoir water are not functioning and only a few borehole-fed gardens are operational. In addition to untold human suffering, the drought has had devastating effects on wildlife, decimating the populations of many species.

In this context the first two collector well gardens in Zimbabwe, one at the Lowveld Research Station and the other at a village in Chivi Province, continue to perform impressively, providing a valuable source of fresh vegetables. The Chivi collector well is also currently providing fresh vegetables for sale and consumption by 46 households and domestic water to over a 1000 non-scheme members. As a result of the success of the project to date, funding has been secured for a further 12 collector well gardens in Zimbabwe and much interest has been shown in the project from researchers and agencies working in other semi-arid areas.

A second component of the Institute's work with the Lowveld Research Station has been developing and quantifying the benefits of simple low-cost techniques to increase water use effectiveness on irrigated gardens. This research involves on-farm trials and has demonstrated that substantial improvements can be achieved by adopting simple techniques such as subsurface irrigation using clay pipes or by using crop residues as a mulch. As water is the limiting factor on the size of groundwater-based irrigated gardens in semi-arid areas, an improvement in water use effectiveness means that the size of the garden can be increased.

A further development is investigation of subsurface movement of water in a Basement Complex area, particularly looking at groundwater recharge and how land-use change affects the surface partitioning of rainfall into infiltration and runoff. The most striking land-use change in this area of Africa is the conversion of grazing land to native agriculture, where severe land degradation problems are currently encountered.

Laying to fallow is the traditional means of resting land after several years of cropping. This works primarily to restore fertility levels in the soil but there may also be hydrological changes, depending on the water use of the natural savannah vegetation which then regrows. Early work on savannah vegetation clearly demonstrated that such vegetation evaporated more water than denuded bare soil areas, but there is a wide range of fallow types and their water use will depend strongly on their vegetation composition. A key component of fallows in west Africa is the dominant woody shrub, *Guiera senegalensis*. The Institute has recently carried out tests using a new device which, when applied to the plant stem, can measure directly the amount of water transpired (see Figure 3). Figure 4 shows the hourly-averaged sap flow rate in a single Guiera stem over a 12-day period following an 18 mm rainfall event. The bushes were almost leafless at that time, just after the start of the wet season. The graph shows the dramatic increase in water-use which accompanied the rapid expansion in leaf area stimulated by the rainfall.

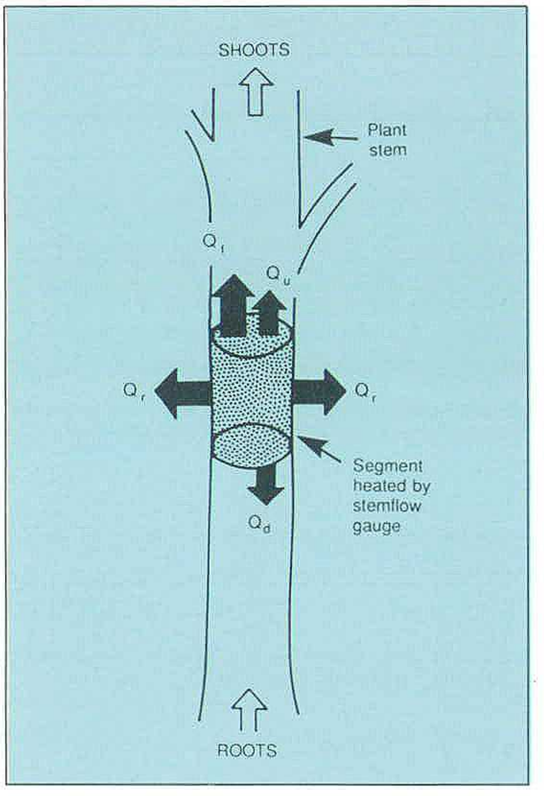
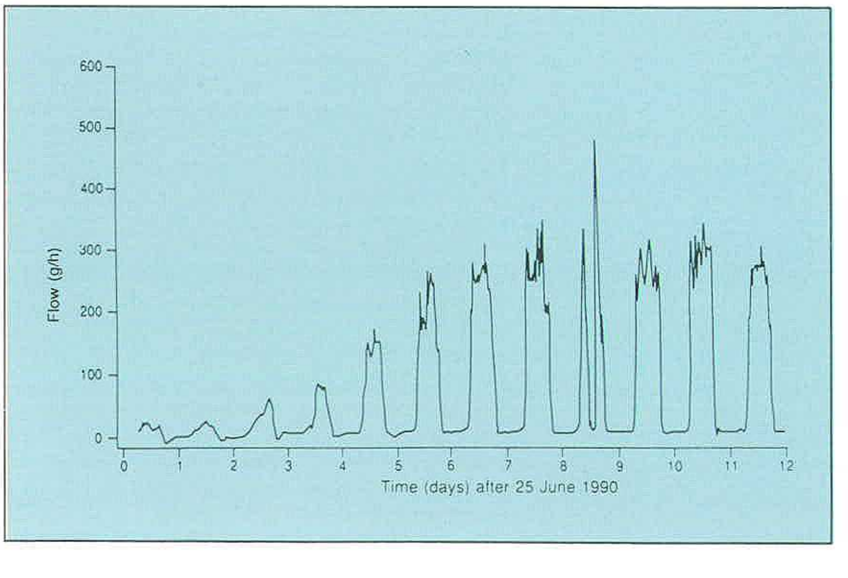


Figure 3 The stem heat balance principle for measuring sap flow in plant stems. A known amount of heat applied to the stem is lost as radial conduction (Q_r), vertical conduction (Q_u and Q_d) and in the sap flow (Q_f). This device is relatively simple to instal and can be left on the plant for several weeks. A further attraction is the ability to record the output of the gauge automatically on modern solid state loggers.

One of the most likely ways of reducing dryland degradation and achieving sustainable land use in the semi-arid tropics is through the use of mixed plant communities which can make more efficient use of natural resources. Agroforestry is a promising example, since the mixing of trees and crops has been demonstrated to have value both in terms of soil conservation and in improving yield. However, the success of a tree/crop option depends on the degree to which the components of the mixture are complementary in their use of water, light and nutrients.

An agroforestry project is now under way to improve understanding of the principles under-

Figure 4 The variation in transpiration in a Guiera bush after the first rains of the 1990 wet season: the sudden decrease in flow rate around noon on day 8 was caused by a rainstorm.



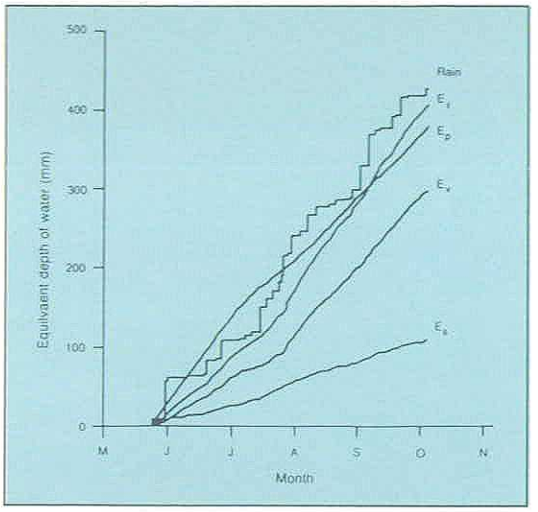


Figure 5 Cumulative rainfall, estimated total evaporation (E_t), modelled soil evaporation (E_s), evaporation from vegetation (by difference) (E_v) and Penman potential evaporation (E_p) for the entire 1990 wet season. This shows that the total evaporation for this vegetation was close to the rainfall input, leaving little water for runoff or recharge in this low rainfall year

lying the partitioning of these resources, in collaboration with the International Center for Research in Agroforestry (ICRAF) and the University of Nottingham. IH will focus on the development and validation of measurement techniques, and on models of the water use of trees and crops grown in combination on sloping land.

Dryland forests are also under threat of degradation. They are sources of wood and fodder and may play a significant role in the water balance of an area by influencing storm runoff and groundwater recharge. A common natural forest in the Sahel region is tiger bush, so-called because the vegetation grows in dense strips, separated by completely bare soil. Monitoring soil water movement in the unsaturated zone and measuring evaporation over the tiger-bush has indicated that there may be less seasonal variation in evaporation from this land type compared with either fallow savannah or millet. This is thought to be associated with deeper rooting of the tiger bush. It also appears that the majority of the rain evaporates from the bushes (see Figure 5).

Even though the tiger bush only covers 33% of the surface, it uses over 70% of the rainfall. Water balance measurements, supported by soil moisture observations, provide strong evidence for a form of 'water harvesting' by the vegetation from the bare soil areas. The conclusion is that these sites are unable to sustain dense woody vegetation over all the land surface but, in the absence of human intervention, the vegetation strips can adjust to long-term shifts in rainfall by adjusting the ratio of bare ground to vegetation cover.

The decrease in the percentage of ground cover in these tiger-bush areas, visible further north in drier climates, is supporting evidence for this. A further conclusion is that it is futile to seek to regenerate complete woody vegetation cover on these sites in this climate. Tiger-bush areas may be sources of runoff and groundwater recharge when rainfall is close to or above average, but our results show that when rainfall is 25% below average there is no significant net runoff or recharge from these areas.

Water use of Eucalypts

The Institute is also monitoring the water use of plantation forest in the tropics. In southern India, where eucalyptus trees are being widely planted as a timber source, the worry is that they might use very large quantities of water, as has been reported from Australia and south Africa. Initial studies of water use of eucalyptus in Karnataka State showed that although they consumed more water than arable crops their water use was no higher than the indigenous dryland forest.

Further studies in a second area showed the (initially) surprising result that the total water use of a eucalyptus plantation was greater than the total rainfall over the three-year measurement period. Since the water table in this area was very deep (30 m) it was concluded that the trees were 'mining' water from progressively deeper layers of soil. Clearly this is an unsustainable system. However, with the additional knowledge of how much recharge the traditional agricultural systems allow, it would be possible to 'design' tree/crop rotations where the deep water mined by the trees was replenished by recharge under cropping. The duration of each part of the rotation could then be adjusted for different rainfall regimes.

Climatic feedback

Where large areas of vegetation are denuded by land degradation processes there is concern that this may be an accelerating process exacerbated by biophysical feedback: several modelling studies have indicated that removal of vegetation may modify the surface energy balance in such a way as to reduce rainfall. Any reduction in rainfall will have serious consequences for agricultural production.

The forecasts from these models are very sensitive to the representation of the land surface and to the presence of vegetation. Unfortunately very few data are available from which to derive descriptions of Sahelian vegetation. The data collected by the Institute from the fallow savannah site in West Africa have been used to improve the 'tropical savannah' parameterisation in the UK Meteorological Office's General Circulation Model. A further improvement has come from including a two-source energy balance model, originally developed at IH for crops but now adapted for savannah vegetation. This physically-realistic model allows for simultaneous (and equally important) fluxes of heat and evaporation from bare soil and vegetation and for interactions between the two. Since over 70% of the world's natural vegetation can be defined as sparse, this is a significant step forward.

Hydrologically, the semi-arid lands of the world rest on the knife-edge of existence. Through its dryland research programme IH seeks to provide some of the understanding necessary to preserve their equilibrium. Population growth weighs against land degradation, and productivity against sustainability — it really is a question of balance.

Tropical rainforest and climate: ABRACOS

Tropical deforestation is a controversial and emotive subject. It involves a very rapid and permanent change from the lush climax vegetation of species-rich rainforest to the featureless landscape of a cattle ranch. One of the many questions raised in the debate about the causes and consequences of deforestation is the effect of deforestation on climate. Does removing the rainforest change the climate? A collaborative study between the Institute and the several Brazilian research institutions aims to provide the answer to that question.

The Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) is funded by the Overseas Development Administration. It is a collaboration between the Institute, the Brazilian National Institutes for Space Research (INPE) and Amazonian Research (INPA) and two agricultural research institutes, CENA and EMBRAPA, with the participation of Brazilian scientists from several other research institutes and universities.

Predictions of the climatic effects of changes in vegetation are made using Global Circulation Models (GCMs), which are used in controlled modelling experiments. The model is first run with a land surface description representing the earth as it is today. The model run is then repeated, with the samo initial conditions, but with the land surface parameters changed. The resulting alteration in climate is interpreted as being the result of the change imposed on the land surface.

Predicting the effects of Amazonian deforestation has been one of the most active areas of research for climate modellers. In general terms the models predict an increase in temperature, a decrease in evaporation and a reduction in rainfall. This decrease in rainfall is predicted to occur mainly as an increase in the length and severity of the dry season. The rainfall over the Amazon basin has been predicted to fall by as much as 25 per cent. Reduction in rainfall has also been predicted for the cerrado, or savannah belt, to the south of the forest, and also in the north-east of Brazil, an area which already suffers serious droughts and where a reduction in rainfall would create severe problems for agriculture.

While there is no doubt that the potential for substantial climate change has been demonstrated by these studies, the model predictions can be no more accurate than the data which were used to calibrate the land surface descriptions in the control and deforested model runs. Between 1983 and 1985 a previous collaborative project between IH, INPA and INPE collected what has now become a classic data set from the Reserva Ducke forest near Manaus, in central Amazonia. The measurements of the radiation balance, the transpiration and the evaporation of intercepted rainfall made in that project have been used to calibrate all the major GCMs currently in use today. The control run of any recent deforestation experiment will therefore have been calibrated against actual data from a site which can probably be taken as being representative of a large area of central Amazonia.

The River Jaru flowing through rainforest in south-west Amazonia. The photograph was taken at 3 o'clock on a September afternoon. At this time of year the smoke-filled atmosphere created by the burning often gives a red sun throughout the day.

The aim of ABRACOS is to collect a similar data set for the cattle ranchland which is replacing the forest. At the same time long-term observations are being made of the differences in climate between forest and ranchland in the areas where deforestation has already occurred. Pairs of climate stations are producing data sets which will be used to test the current formulations in the GCMs to see how well they reproduce the observed climate and the changes which might occur following deforestation.

Each of the components of the surface energy and water balances needs to be measured separately and modelled in terms of the parameters required for GCMs. Incoming solar radiation and how much is reflected from the surface are two important measurements. The evaporation and the ratio of evaporation to the flux of sensible (or convective) heat are also important: they determine not only the amount of water vapour returned to the atmosphere, which is then available to fall as rain, but also the energy available for extending the depth of the atmospheric boundary layer. This may be an important factor in determining cloud formation and the consequent initiation of convective storms. Soil moisture and plant physiological measurements are made so that the evaporation measurements can be interpreted in terms of the environmental variables which are controlling the vegetation, and so that the representativeness of the results can be assessed.

Experimental sites

ABRACOS has three sites across Amazonia (see Figure 6). During the first two years of the project, work was concentrated in a clearing and in the forest close to Manaus in central Amazonia. Two other sites have since been established. One is near Marabá in the state of Pará, close to the eastern edge of the forest; the other is near Ji-Paraná in the state of Rondonia, close to the southern edge. The major effort is now being directed towards these sites. Being nearer to the edge of the forest, these sites are in areas in which there is a longer and more pronounced dry season. This increases the likelihood of substantial soil moisture deficits developing and gives the opportunity to study the vegetation under water stress. Unlike the site near Manaus, where there has been relatively little forest clearance, the sites at Marabá and Ji-Paraná are in areas where there has been substantial clearing. Measurements at Manaus therefore give the effect of vegetation change alone, whereas at the other sites there is also the possibility of observing differences caused by the interaction of larger-scale clearance with the atmosphere.

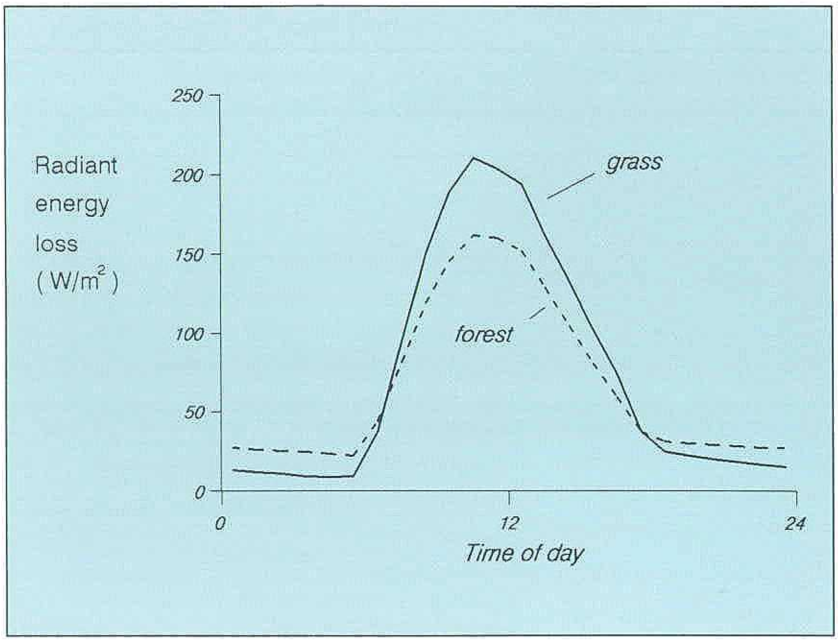


Figure 7 The radiant energy lost from the ground is greater for pastureland than for forest

Figure 6 Locations of the ABRACOS study sites

Surface energy differences

Forest reflects less of the incident solar radiation than grass. The radiation is trapped by multiple reflections within the deep forest canopy. The Amazonian ranchland reflects about twice as much solar radiation back into the atmosphere as does the rainforest. The forest also gives off less infra-red radiation. The rough forest surface creates a strongly turbulent airstream which prevents the creation of large surface-air temperature differences. The surface of the grass, on the other hand, can become relatively hot: 10°C above air temperature is not uncommon. This results in a greater loss of infra-red radiation from the grass, so that grass both reflects and emits more radiation. The effect of this can be seen in Figure 7 which compares the total radiant energy loss from the ABRACOS ranchland and forest sites near Manaus.

The grassland has less energy available to use either for evaporating water or for converting to sensible heat. This reduction in energy at the surface means less energy to drive atmospheric weather systems and the possibility of permanent changes in weather patterns.

One factor not previously considered has been the change in the reflected solar radiation following grass burning. Annual burning of the pasture is common management practice on the ranches of Amazonia: it destroys forest regrowth and encourages new growth by the grass. However the burnt grass is a good absorber of solar radiation (see Figure 8) and this practice will act to reduce differences in the long-term energy balances of the vegetation types.

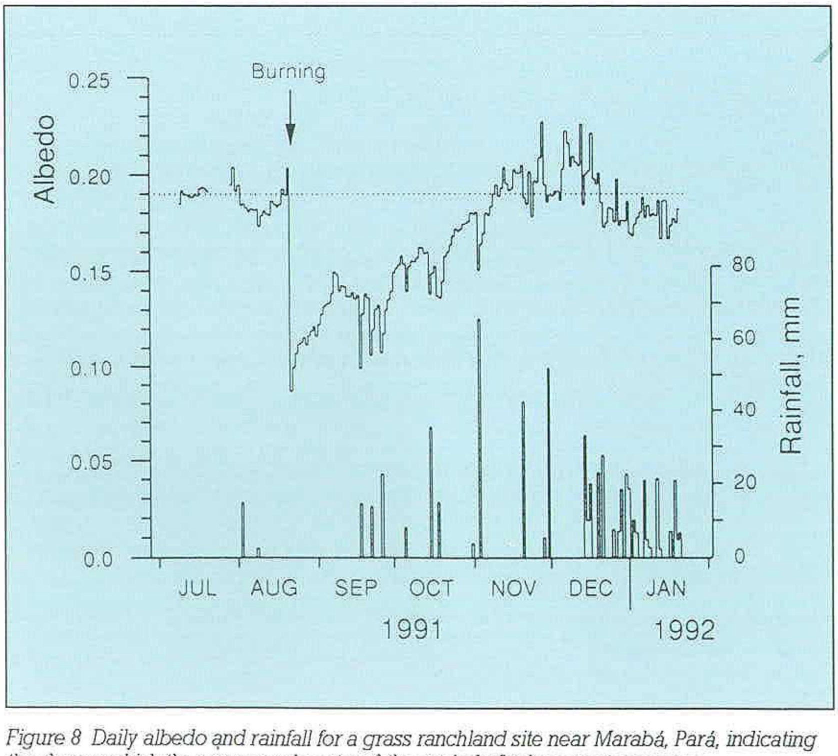


Figure 8 Daily albedo and rainfall for a grass ranchland site near Marabá, Pará, indicating the day on which the grass was burnt and the period of subsequent recovery

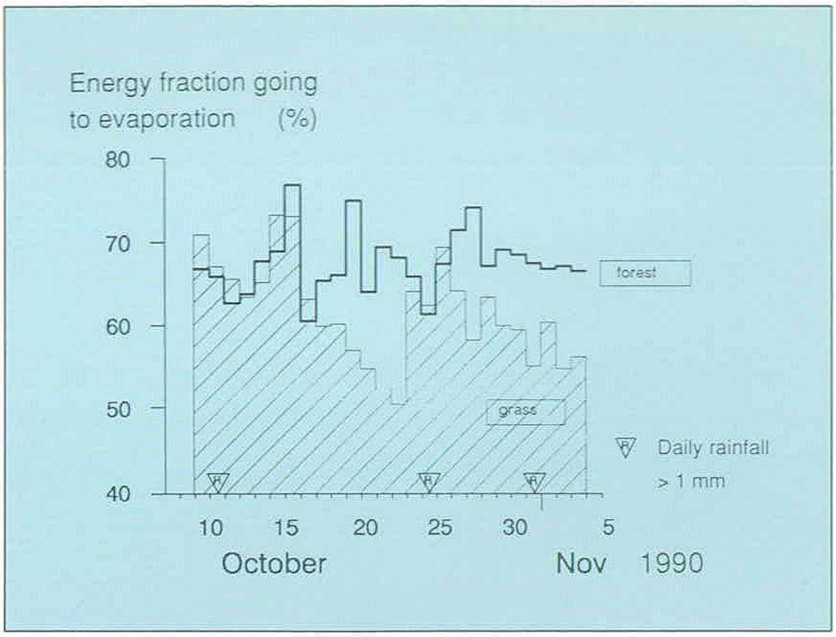


Figure 9 In dry spells the fraction of energy used for evaporating water from pastureland falls more quickly than for forests

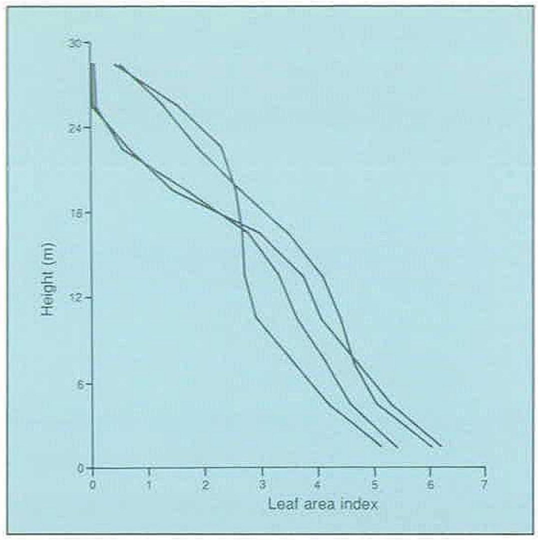


Figure 11 Cumulative leaf area index against height in four 100 m² plots of terra firme *rainforest near Manaus, central Amazon*

Evaporation differences

Results of the measurements in central Amazonia show that when there is no shortage of moisture in the soil, evaporation from the grassland and forest is similar, but that in dry periods they behave very differently. After about ten days without rain, evaporation from the grass starts to fall as the small amount of water accessible to the shallow roots is quickly used up (see Figure 9). In contrast, the deeper rooted forest continues to evaporate water at much the same rate as before. This different response is confirmed by the soil moisture measurements which show greater extraction by roots below one metre under the forest (Figure 10).

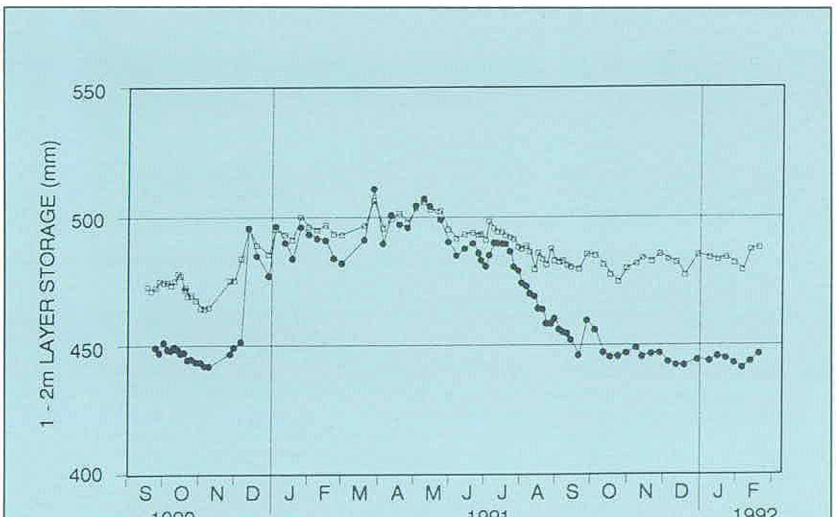


Figure 10 Graph showing greater extraction of soil moisture by roots below one metre under the forest.

Measurements of the biomass and leaf area: The Carbon Store

One of the indirect ways in which deforestation acts to change climate is by contributing to greenhouse warming. The carbon stored in the biomass of the forest is released as carbon dioxide during deforestation, either rapidly by burning or more slowly by the removal and subsequent decay of the timber.

There is great uncertainty about the amounts of carbon being released in this way, with little quantitative data from which to produce statistics. One ambitious task of the ABRACOS field campaigns has been to measure in detail the amount of wood and leaves in a representative 20m x 20m plot of forest. The leaf area index and the total weight of the above ground biomass have been measured by destructive sampling. From a comparison of four plots in the forest, Figure 11 shows that although there is substantial variation in the vertical distribution of leaf area, there is relatively little variation in the horizontal. The total leaf area index has an average of 5.7 $m^2\ m^{-2}$. These measurements will be invaluable both in modelling the ecological behaviour of the forest and in assessing the carbon released when it is felled.


TOYOTA
A100 HKF
D155 YRK

Floods: anticipating acts of God

Floods are amongst the world's most devastating natural hazards, claiming thousands of lives each year, destroying property, disrupting communications and ruining agricultural land. Almost all climatic regions suffer from flooding, although the frequency and severity of flooding varies widely: human activity tends to increase flood runoff through deforestation, land drainage, urbanisation and road building.

Hydrology has a central role to play in understanding the processes of flood generation and the statistics of extreme events in order to assess flood risk and guide the design of flood alleviation and flood warning schemes. Research at IH established the standard reference for design flood estimation in the UK with the publication of the *Flood Studies Report* (FSR) in 1975. The continuing programme of fundamental research is yielding two major developments. The expertise in flood estimation built up during the Flood Study is now being applied to exporting know-how from the UK to areas of the world with little or no flood data. In sharp contrast, the second development concerns data-rich applications to real-time flood forecasting systems designed to predict the actual flood hydrograph a short time in advance in support of flood warning and control. Here the Institute is developing state-of-the-art models and software: in partnership with industry it is providing some of the world's most advanced flood warning systems for the National Rivers Authority and exploring overseas markets.

A flooded road near the River Thames

Flood estimation

In view of the growing damage to life and property caused by flooding in the developing world, much of the Institute's work has concentrated on providing better tools for estimating flood magnitude in regions with little or no data. The aim is to provide a simple, robust and consistent methodology for estimating flood peaks of any required risk of exceedence, or return period, so that engineers and planners may develop appropriate flood protection measures and have a basis for the design of new works.

Local data must be analysed in order to calibrate the models, which are an extension of the statistical methods described in the Flood Studies Report. a dimensionless regional flood frequency curve is combined with a prediction equation for the mean annual flood, or *MAF*. Because of the limited data available the prediction equations for the *MAF* are based on catchment area *AREA*, and mean annual rainfall *AAR* alone. Data have so far been collected from some 80 countries around the world from over 2500 stations and in all some 35,000 station years of data have been analysed.

Our research has sought to develop prediction methods, particularly for arid and semi-arid regions. A range of flood frequency curves and *MAF* prediction equations has been produced from those countries or regions where some data are available and the following overall equation has been proposed.

$$MAF = 0.172\ AREA^{0.573}\ AAR^{0.418} \qquad R^2 = 0.57$$

This equation has a rather high factorial standard error of estimate of 2.85, although some of the individual country or regional equations have a factorial error of less than 1.5, and R^2 values in excess of 0.9.

Some regional flood growth curves are shown in Figure 12. The high curvature of the general extreme value type 2 curve results from the few occasions when rainfall intensities are sufficiently high and spatially extensive to cause widespread flooding. In many years, rainfall may not be sufficient to exceed the soil's infiltration capacity, and runoff may be viewed as occurring only when some fixed soil moisture capacity has been exceeded. It seems likely that the runoff process will be non-linear, with a dramatic increase in runoff from storms exceeding some threshold and also where storms are sufficiently widespread to generate runoff from a significant proportion of the catchment.

Work has also been carried out for a large group of countries in West Africa, ranging from Senegal to Cameroun, and a series of prediction equations has been prepared. The main effort to extend the project is in collecting data from regions of the developing world which currently lack appropriate flood estimation methodologies. The work is being directed particularly towards East Africa, India, Pakistan, Nepal, and Central and South America.

Real-time flow forecasting

Real-time flood forecasting systems aim to predict the actual flood hydrograph a short time ahead in support of flood warning and control. They rely on access to up-to-date information on river levels, rainfall and other hydrometric data to maintain the accuracy of flood forecasts. There is also a growing requirement for flow forecasting systems which provide predictions not only of floods but over the full range of flows. Such forecasts are required for extended lead times, often several days or even months ahead, to support decision-making concerning drought management, intake protection and pollution control. They pose new challenges in model formulation and software design.

The history of the Institute of Hydrology's development of real-time flood forecasting systems began in 1974 with the Dee Research Programme. This was the first flood forecasting system to use rainfall data from UK weather radar. A programme of basic research funded by NERC in the second half of the 1980s led to innovations in model formulation and, particularly, in updating techniques. These updating techniques incorporate recent flow measurements from telemetry into the model to improve its forecast of flow, either by internal state adjustment or by external error prediction. This work continued under Ministry of Agriculture Fisheries and Food funding and more recently returned to improving the use of weather radar rainfall estimates in flood forecasting models.

In 1988 the Institute was awarded the contract to develop the hydrological kernel of the Yorkshire Region forecasting system, covering an area of 13,500 km^2; Logica Industry Ltd was responsible for the shell of the system (database, interfaces to telemetry and users). This provided the opportunity to consolidate previous research and produce a generic, reconfigurable flood forecasting system. The IH River Flood Forecasting System (RFFS) consists of an information control algorithm for operational generation of forecasts and also facilities to calibrate models using historical data. The Yorkshire RFFS completed its tests in 1991 and has been operational since the start of 1992; the software has been in considerable demand within the UK and overseas.

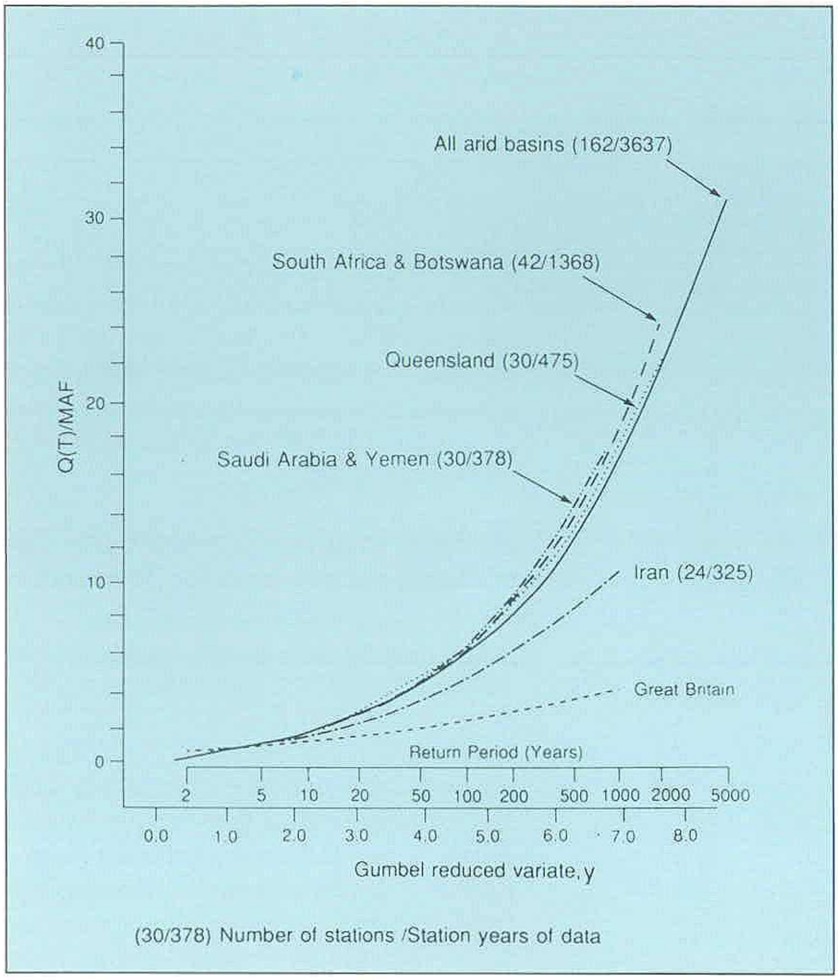


Figure 12 A range of flood frequency curves

The RFFS offers a range of functionality not present in other systems. As well as incorporating models designed to operate over the full flow range, a generic algorithm structure allows new model formulations to be added as requirements change or advances in modelling are made. The algorithms currently available range from setting a constant value to represent a reservoir compensation release, to models representing snowmelt, catchment runoff, and channel flow in non-tidal and tidal river reaches.

The hydrological channel flow routing model KW, based on a kinematic wave formulation, allows for flow-dependent wave speeds, washland storage attenuation and embedded stage-discharge relations through simple empirical functions. It can be calibrated without expensive survey data. At the other extreme of complexity, a hydrodynamic model based on the one-dimensional Saint-Venant equations is available for tidal river modelling. In this case the generic model algorithm structure has allowed a gate control rule to be incorporated within the overall formulation: an example of gate control and level forecast using this rule is shown in Figure 13.

All the models are provided with updating facilities which allow recent telemetered data to be used to improve model forecasts. In the case of snowmelt and rainfall-runoff models internal adjustments are made to the water contents of conceptual stores within the models to make the model output accord better with observed values. For models involving channel flow, simple error predictors are used which aim to predict future errors based on the dependence seen in present and past model errors: these predicted errors are then used to improve the initial forecasts.

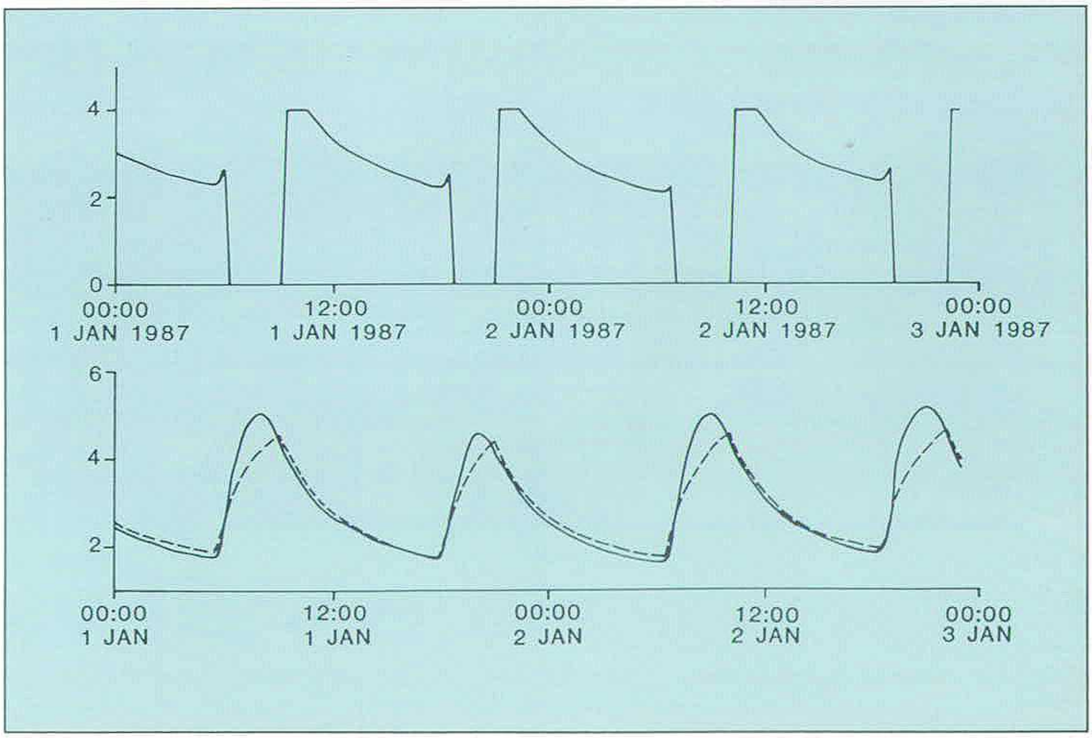
Not only is the RFFS configurable in terms of model algorithms, but it can also be configured to any river network without extensive recoding. Furthermore, an existing model for a river network can be modified to accommodate, for example, new telemetered river gauging sites. This is achieved through the use of the Information Control Algorithm (ICA) which uses a data-defined model network structure to control access to telemetry data required to make forecasts, and to control the sequential execution of the models working down the river system.

It is also possible to select only parts of a complex river network model to be run, through the concept of user-defined subnetworks. These can be configured to invoke only forecasts of head-water catchments for flash flood forecasting: running a time-consuming tidal hydraulic model is thereby avoided and frequent forecast updates can be made. During the production of the forecast the near-current values of the state variables, such as water contents in the various model stores, are stored and used in initialising subsequent model runs, thus avoiding a long "warm-up" period.

The NRA Yorkshire Region RFFS currently meets 183 primary forecast requirements. The system is supported within a VAX-based shell of database and interfaces developed by Logica. The RFFS's configurability and transportability has been demonstrated through its use as the basis of the White Cart Water Flood Forecasting System, providing flood warning to the southern parts of Glasgow. This system runs on the Clyde River Purification Board's computer, making forecasts for seven sites supported by telemetry data from six river gauging stations and four raingauge stations.

The RFFS kernel software is currently being developed for use in Hong Kong: a pilot flood forecasting system, to be run on a SUN UNIX work-station, has been commissioned for the Indus basin. A strategy is also being worked out for its implementation throughout the Anglian region of the NRA, where more than 1000 requirements for flow forecasts have been identified, both at high and at low flows. The Anglian Flow Modelling System aims to provide a unified "Windows" environment for water management during floods, droughts and water pollution incidents through to the next century.

Figure 13 Simulation of the automatic control of the Derwent tidal barrier within the Yorkshire River Flow Forecasting System. The top graph shows the gate closing as the tidal River Ouse (solid line below) rises: the River Derwent (dashed line) rises less as a result.



Wetlands: areas of hydrological excess

The processes of surface runoff and infiltration into the ground are normally effective in removing excess water from the land. Where these processes are impeded, wetland habitats, with their moist or permanently saturated soils, may develop. Plant life in wetlands is highly specialised in order to cope with excess water, lack of oxygen and frequently a scarcity of nutrients in the soil. The rural economy of wetland areas is also distinctive, based on drainage and careful water level control, or on the cultivation of wetland crops such as rice and freshwater fish, and the production of traditional materials including reed and peat. If we are to conserve these wetland areas, it is vital that we understand their hydrology.

Wetlands, which have become scarce resources in many countries, are highly valued natural habitats many UK wetlands have been given the protective status of Sites of Special Scientific Interest (SSSI) as botanical and ornithological reserves. The long-term preservation of organic remains in peat and other saturated deposits has important implications for archaeology and Quaternary studies, which have also added weight to the case for preservation of wetland sites.

In the face of development and agricultural improvement, which threaten to change the groundwater regime through excavation or deliberate drainage, a good understanding of the hydrology of wetland sites is an essential foundation for their conservation. Wetlands can also have important effects on the quality of streamflow, and current work at IH is aimed at providing a fuller account of the movement of both water and chemical ions through wetland soils.

Studies of the hydrology of wetland sites

With the support of the Ministry of Agriculture, Fisheries and Food (MAFF), and drawing on experience and data from sites managed by the Nature Conservancy Council (NCC) and its successor bodies, the Institute has investigated some of the more important aspects of wetland hydrology. The aim of the work has been to understand the response of wetlands to natural cycles of climate, as an aid to predicting their response to externally-imposed stresses.

View of the lower half of the Ceunant Ddu subcatchment, mid-Wales, showing the wetland area within the young forest and the flow measuring structure for the upper half of the catchment

The water budget of many wetlands is dominated by precipitation and evaporation; water is stored in the saturated zone of the soil. Many wetland plants are phreatophytes, i.e. they are able to draw directly on groundwater to meet transpiration needs. The permeability of the soil is generally low. This limits the horizontal movement of water to and from the stream network and other open water bodies; summer water levels are determined largely by the evaporative demand, with occasional rises in the water table caused by heavy summer rainfall. Lateral groundwater flows, which re-distribute water across the site, can be detected and quantified by examining the variation of the groundwater level on a variety of time scales. Computer modelling techniques can be used to improve estimates of lateral flow. For instance Figure 14, based on the output from a digital groundwater model, gives a clear picture of the seasonal variation of lateral groundwater flow to and from a water-filled dyke (or rhyne) system on West Sedgemoor, Somerset.

The complication introduced into the water balance by lateral flows through the soil can be removed by enclosing a block of soil, complete with its vegetation, in a lysimeter. This technique makes it possible to study the response of the groundwater to the *vertical* components of the water balance, rainfall and evaporation. Automated lysimeters, using micro-computers to control water levels and pump precisely-metered quantities of water, have been used at two sites to determine actual transpiration on a daily basis. The results, which corroborate others obtained from water level measurement only, suggest that the amount of dead material in the standing crop of natural or semi-natural communities in wetlands, e.g. reed stems from previous years, reduces transpiration rates to below the potential evapotranspiration. A grazed and mown wetland site, West Sedgemoor in Somerset, was found to transpire at nearly the potential rate. This conclusion agreed well with the results from three independent methods for estimating the actual transpiration.

Simpler techniques can sometimes be equally effective: the detailed analysis of continuous or frequent (e.g. hourly) water level measurements can also yield estimates of the actual transpiration

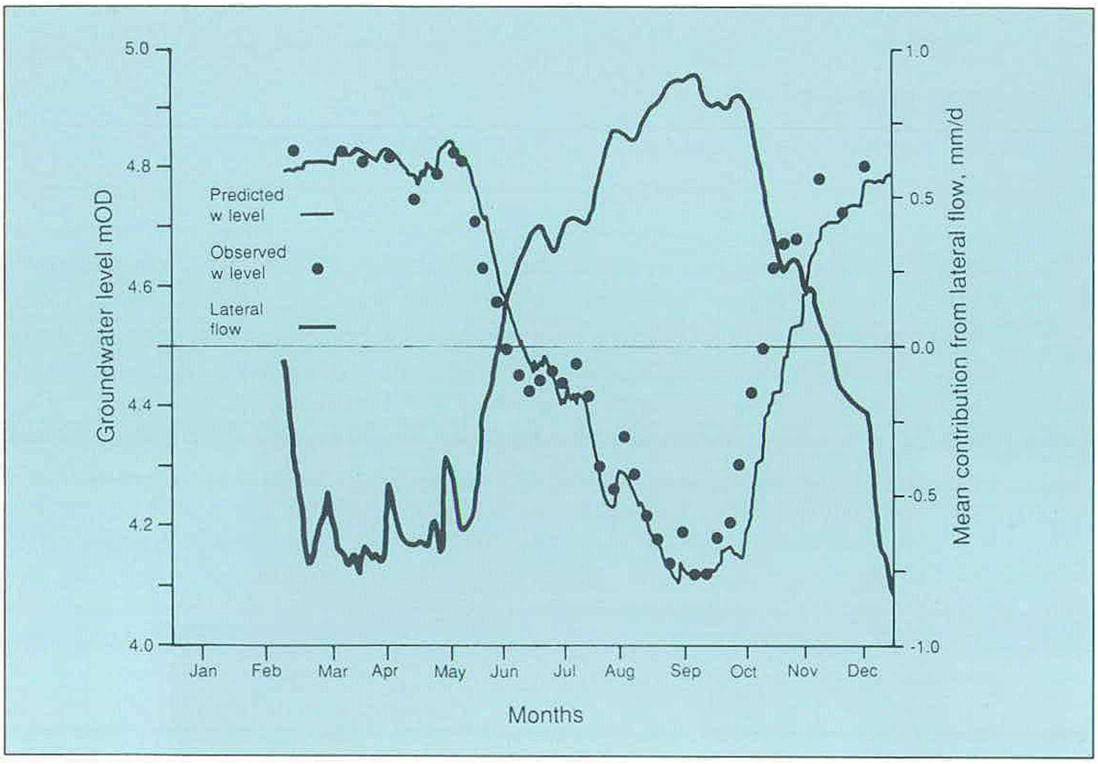


Figure 14 The lateral flow of groundwater from a dyke (rhyne) on West Sedgemoor, computed from model results. The groundwater levels are 52 m from the edge of the rhyne. The lateral flow comp-onent is inversely related to groundwater level, changing sign in late spring and autumn. The maximum lateral flow from the dyke in late summer (just under 1 mm d^{-1}) should be compared with the highest potential evaporation rate of 6.7 mm d^{-1} corresponding to an actual evaporation of about 5.0 mm d^{-1}.

of wetland plant communities. Figure 15 shows actual transpiration rates from "litter" (a fen community dominated by common reed and purple moor-grass) at Wicken Fen, Cambridgeshire. The results were computed from continuous water level measurements, using the response of the water table to rainfall to estimate the specific yield of the peat. The litter is cut at two-yearly intervals: before cutting in July 1985 transpiration was a very small fraction of the potential, the mature litter comprising largely dead material. In August the new green crop was transpiring freely. September's results were anomalous because of a significant gap in the continuous record of water levels. The effects of the removal of dead material were still visible in the data from June 1986.

The Llanbrynmair Moor afforestation and the Cerrig-yr-Wyn climatic manipulation studies

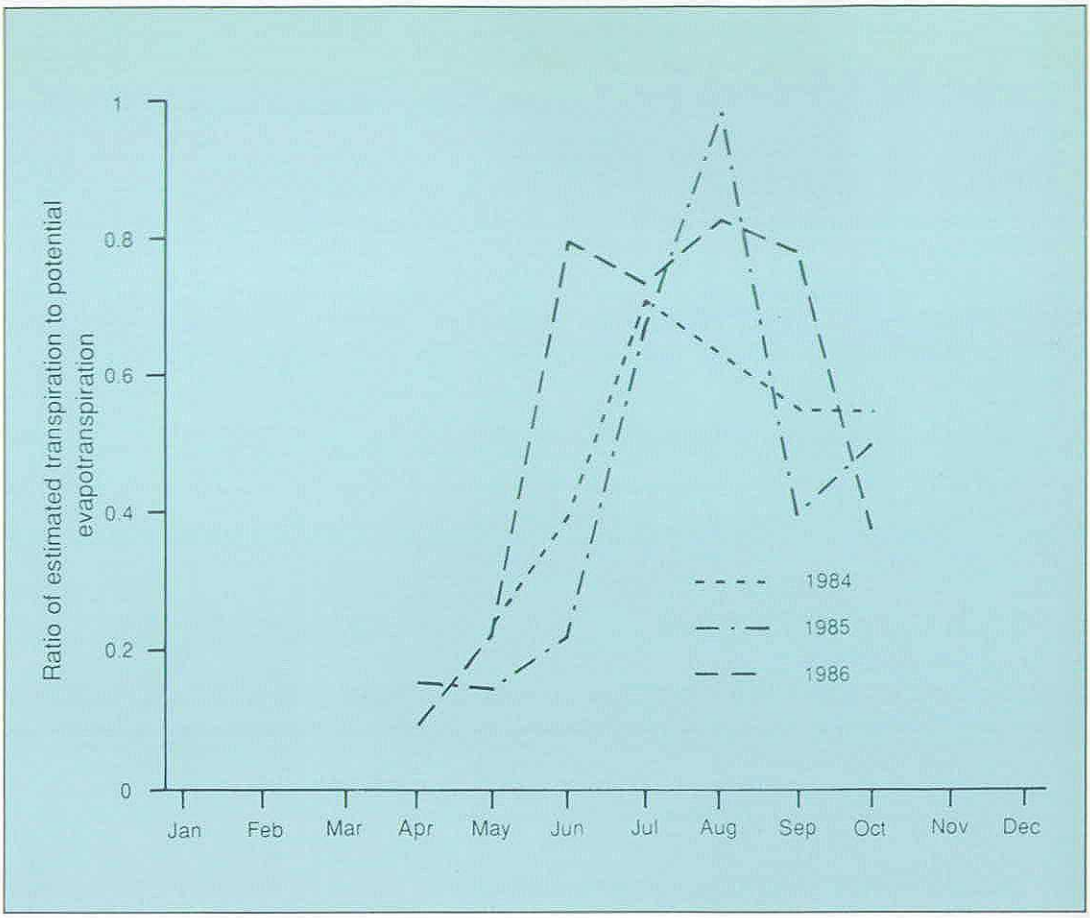
During early investigations of the spatial diversity of chemical characteristics in streams in the Institute's experimental catchments at Plynlimon, mid-Wales, it was realised that solutes released from hillslopes, particularly those suffering some land-use disturbance, did not necessarily reach the streams in the same quantities as were being lost from individual patches of land. Rather than simple mixing of water in parallel channel systems, there appeared to be serial processes working to moderate higher concentrations of solutes, particularly nutrients, as they moved downslope or downstream through areas of water convergence in the riparian zone.

These processes could be viewed as natural safety valves for preventing wholesale pollution of upland water courses and reservoirs, and for maintaining the dilution role of upland streamflow. Such information introduces the possibility of forestry and agricultural management of riparian zones that could accommodate the most pressing environmental standards. However, the circumstantial evidence available at that time was not sufficient to form guidelines of good environmental practice. Further work was required to identify the processes of water and solute transfer through the riparian zone that could form the basis of passive and proactive land management to minimise pollution.

Other indirect suggestions of water quality amelioration in areas of newly planted forest came from the Institute's afforestation study on Llanbrynmair Moor, mid-Wales. This study was designed primarily to look at the initial, catchment-scale impacts of afforestation practices on streamflow, water chemistry and sediment. Samples taken within the Cwm experimental catchment indicated that the overall loss of nutrients from the Ceunant Ddu subcatchment was complicated by releases of nitrate, ammonia and phosphate in downslope ploughlines that were subsequently immobilised before the catchment outlet.

As the lower half of the catchment contained a small riparian wetland, more intensive work was carried out from 1989 to 1991 to follow the workings of the catchment: ploughline processes, wetland processes and the action of the wetland on streamflow passing through it. In spite of its small size — 5% of the catchment area — and the relatively short retention times in the mire, there was also evidence of short-term reductions in nitrogen and a clear change from oxidised to reduced forms. However this was followed in the study period by flushes of nitrogen, particularly during the dry summer of 1990.

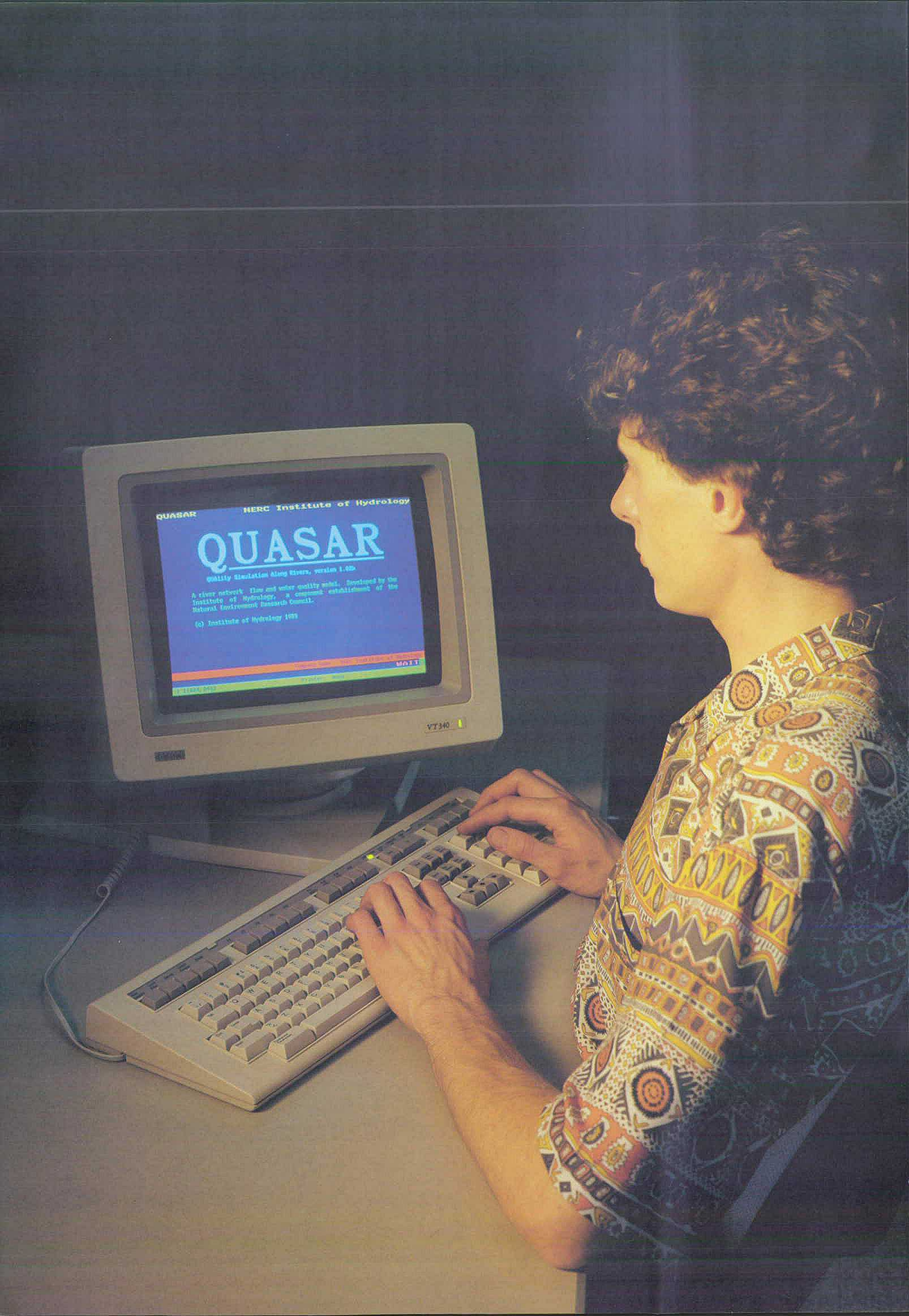
Figure 15 Actual transpiration rates from "litter" at Wicken Fen, Cambridgeshire, over three summers. Litter is cut at two-yearly intervals: before cutting in July 1985, transpiration was a very small fraction of the potential but by August the new green crop was transpiring freely.



It became clear that the response of the wetland and its solute reduction capability depended on the climatic variability, with dry summers tending to undo the good work of wetter periods. Scenarios of climate change to drier and warmer summers led to speculation that there would be a gradual degradation of the mire, in the short term, by mechanical, fluvial and chemical weathering, which would, in the long term, lead to loss of the wetland itself.

The wetland at Llanbrynmair is too large and the catchment system too complicated hydrologically to contemplate large-scale manipulation to simulate climatic change. Instead, a simpler linear flush system was found at Cerrig-yr-Wyn in the Wye catchment at Plynlimon. Here, during the summers of 1991 and 1992, a portion of rush-and-sphagnum channel-mire has been isolated hydrologically and allowed to dry out by artificial means. Flows through and around the mire have been measured and the physical and chemical characteristics of the streamwater monitored, to be compared with similar measurements from an undisturbed control mire. Monitoring techniques include continuous measurements of flow, pH, conductivity, temperature, redox and dissolved oxygen in the main stream, soil temperatures in the control and experimental flushes, flow-proportional sampling at three points in the study area and rainfall and climate in the proximity of the catchment.

The Institute of Terrestrial Ecology (Bangor) are joint contractors in the study: they are providing the measurements of losses of greenhouse gases NO_x, CH_4 and CO_2 from the flushes, estimates of changes in soil water chemistry using suction samplers, and productivity estimates of the autotrophic communities of algae and bacteria, the main biological indicator species in such ecosystems.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Runoff modelling: processes at the catchment scale

Although only a small proportion of the earth's water is found in rivers, in terms of its impact on human activities, surface runoff is one of the most important hydrological processes. A major objective of hydrological science is the quest for a sound quantitative understanding of the relationship between surface runoff and the precipitation which causes it. This scientific understanding leads to better prediction of floods, reduced river flows, and the transport of material in solution or suspension in runoff. It should also provide a means of estimating with some confidence the likely effects on runoff of changes in catchment characteristics, such as land use, or changes in climate.

Surface runoff is ultimately derived from that part of precipitation which is not returned to the atmosphere by evaporation. It depends both on direct runoff of precipitation, and on the progress of water infiltrating soil or rock before returning to the surface. However, a full hydraulic description of these processes at catchment scale in terms of the equations of conservation of mass, momentum and energy is neither possible nor desirable. Instead, hydrologists attempt to model catchment runoff using suitable approximations which balance model simplicity with good process representation or predictive accuracy, often with a close view to the potential model application. In particular, the model must account for the attenuation and delay in the catchment response to precipitation. In physical terms the response is determined largely by the resistance of the catchment to the passage of water, its capacity to retain water, and the extent of any catchment losses other than surface runoff. Runoff models differ in the scale and the manner in which these characteristics are defined.

The key components of most models, at whatever scale they are defined, are a water balance equation and a relationship — possibly indirect — between the discharge at a location and the amount of water present. This relationship is often taken to be linear (as in most time series models) or following a non-linear law (as in the kinematic wave model) and will normally include a parameter which can be viewed as conductivity. Models are commonly compartmental, with equations describing the movement of water between compartments. Even when models are defined in continuous time and space, they are usually solved by numerical methods involving discretisation to compartments. A model will thus include definitions of:

- Compartmental structure
- Time-scale for water movement
- Rules for the transfer of water between compartments, based on an approximation of the dynamics of water movement.

The IH QUASAR (QUAlity Simulation Along Rivers) model in use

Models with many compartments are commonly termed "distributed" while those with only a few are described as "lumped", although these terms have no precise definition.

The progress of hydrological science requires that the relationship between runoff modelling approaches at different scales be clarified, that the limitations of all the various approaches be acknowledged and, if possible, quantified. These are two of the underlying scientific goals of runoff modelling research at the Institute, while progress continues with the application of particular models to pressing current hydrological and environmental problems.

Recent developments at IH have focused on a variety of perceived scientific and engineering objectives. Three examples of different types of modelling approaches are given here, with a further contribution on advances in database archives of catchment characteristics. These database advances not only facilitate the quicker use of existing models, but open up the possibility of developing a new generation of distributed catchment models.

Continental-scale hydrological modelling

One major scientific requirement of current global significance is to provide a suitable description of runoff to interface with General Circulation Models (GCMs). The underlying concern is to quantify the partition of precipitation into that which is lost to runoff and that which returns to the atmosphere through evaporation (largely as evapotranspiration). A continental-scale runoff and evaporation model is being developed as part of NERC's Terrestrial Initiative on Global Environmental Research (TIGER) programme. This will be based on measurable catchment characteristics including topography and vegetation, with rules for water transfer between GCM land surface grid cells which constitute the model compartments. The evapotranspiration component will be described using a SVATS (soil-vegetation-atmosphere transfer scheme) model. The full model will also include a linkage between surface water and groundwater and — as well as interfacing with GCMs — it will also be used to estimate the impact of climate change on water resources.

The Institute of Hydrology Distributed Model (IHDM)

In the IHDM the Institute has a detailed model of soil water processes within hillslopes linked to a stream runoff model which provides a comprehensive description of a catchment's hydrological response. The compartments of this model are blocks of soil within a hillslope and stream reaches (see Figure 16), with transfer rules based on movement down a hydraulic gradient according to the hydraulic conductivity of the soil. Given the inputs of rainfall data, initial soil water content, initial stream flow, and field measurements of catchment characteristics, the model can generate flows directly without calibration based on past rainfall and runoff records (though this may be desirable to improve model performance). The model's structure allows it, in principle, to be used to estimate the effects of both land-use and climate change. Seen in its early days as a research model only, the IHDM is currently being developed for use in engineering and environmental applications under MAFF funding.

The model can be used in either "event" or "continuous" mode and it has recently been used to test model performance over several seasons. Individual components of the water balance can be distinguished, including evapotranspiration, soil water status, surface and subsurface flow rates and residence time in particular parts of the catchment. An alternative approach has used the IHDM to produce nomograms for prediction at given sites: of these, the non-dimensional form allows consideration of a wide range of storm characteristics and soil conductivities for a given hillslope or small catchment.

Lumped modelling approaches

The third example of a modelling approach is one of the least complex. The model here is known as IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) and has compartments which are implicit in its time series structure, consisting in most cases of a "fast" and a "slow" store of water in a catchment. The speed of release of these stores is inferred from model calibration using historical data. The model may be applied on a selected catchment for which there are existing flow, rainfall and temperature records, and is able to characterise the dynamics of both small (<1 km^2) and large catchments. Development of this model has continued in collaboration with the Australian National University's Centre for Resource and Environmental Studies.

Figure 17 shows an IHACRES model simulation of monthly flows for the River Thames at Kingston (catchment area 9948 km^2) for the period between August 1884 and April 1951. The six-parameter model, calibrated using the record from August 1953 to September 1989, is a good characterisation of the monthly flow regime throughout the whole period of record from August 1884 onwards. The Thames rainfall and streamflow data were obtained from the NERC National Water Archive at IH which stores similar data — mostly at a daily time step — for over 1000 catchments throughout the UK.

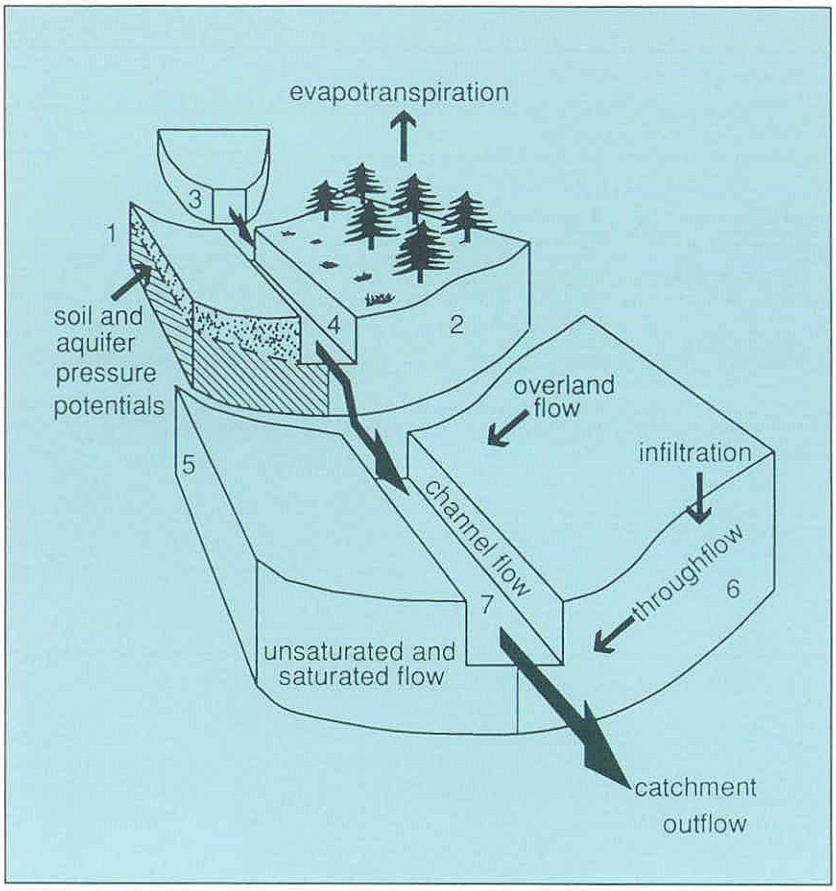


Figure 16 Schematic structure of hillslope and channel components of the IHDM (the numbering indicates the order of the simulation elements)

Four of the model parameters define the unit hydrographs of quick and slow streamflow components. Provisional estimates of corresponding characteristic decay times for the Kingston catchment are 1.28 and 19.2 months respectively. Work is continuing to investigate how these and other IHACRES dynamic response characteristics are related to physical catchment descriptors. The only inputs to IHACRES, when used for the simulation of streamflow, are rainfall and temperature data. Subject to the availability of these data, therefore, streamflow records can be extended back in time to assist with climate change impact studies. Likewise, climate change scenario perturbations can be applied to the rainfall and temperature records to assess the impact on river regime.

Water Information System

Essential support for rainfall-runoff modelling studies is a comprehensive database. The Water Information System (WIS) developed jointly by IH and ICL, is a complete system of hardware, software and supporting services for storing

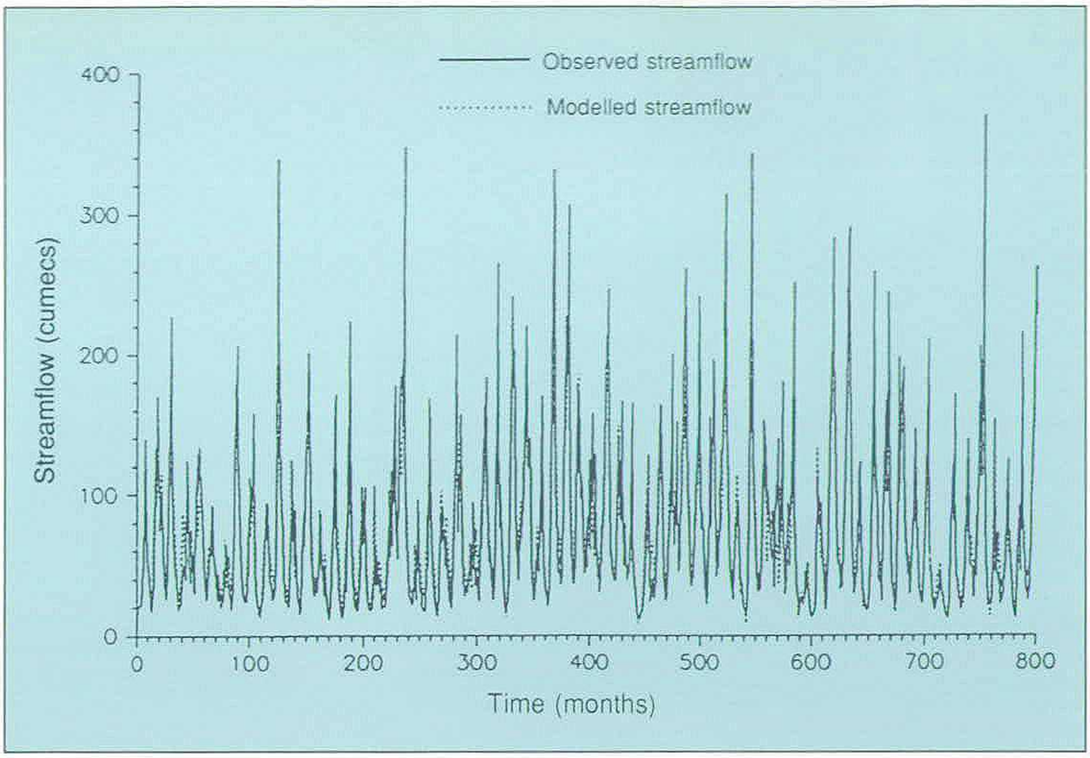


Figure 17 An IHACRES model simulation of monthly flows, compared to the observed streamflow, for the River Thames at Kingston, August 1884 to April 1951

scientific and technical information about the natural and man-made environments.

At its heart is a single database design capable of handling a wide variety of geographically dispersed information which varies with time. Surrounding the database is an increasing range of generic and specific applications for data capture, editing, storage, analysis and presentation. Since the natural and man-made environments operate as an integrated whole, it made sense to concentrate on a single system capable of handling most environmental and industrial data, all of which have a time dimension.

WIS allows the user to record the history of any object or feature as it moves through space and time. A feature's history may comprise numeric, textual and graphical information. An important point is that WIS treats all types of data as though they were a time-series. Everything may, if the user wishes, change with time, including data often considered immutable such as spatial data.

Applications for WIS include catchment characteristic derivation which allows the user to compute catchment characteristics such as rain-fall, soil type or potential evaporation, for use in estimating floods and low flows at ungauged sites. The user identifies the catchment of interest either by deriving it from a digital terrain model, or by selecting a stored boundary, or by drawing it freehand. Values of required characteristics may then be obtained by selecting from a menu. The areas for which characteristics are to be computed do not have to be catchment areas; they could equally well be water supply zones or health authority regions.

The development of a hydrologically appropriate digital terrain model (DTM) is now coming to fruition at IH. This forms a 50m x 50m grid of heights over the entire UK land surface. The digitised river network dictates valley form; modelling of coastal plains and the inter-tidal zone is aided by incorporating tidal range data.

One of the first applications is to derive a catchment boundary for any point on the land surface. This catchment boundary then provides the basis for extracting other data in digital form, such as rainfall or soil type. Information on slope — and therefore drainage direction — is implicit in this model, allowing the development of new catchment characteristics. For example, detailed slope, aspect and elevation data will help to improve estimation of snowmelt rate; the analysis of climate, land use, soil, terrain and the river network should allow the identification of the areas at greatest risk from acid deposition.

Water quality systems: modelling and management

At the Earth Summit on the Environment and Development held in Brazil in 1992, all the national representatives agreed that trans-boundary pollution of air and water was a problem common to virtually all countries. Coordinated and urgent action is required where rivers are used both for water supply and for effluent disposal. Here in the UK, water quality issues have become increasingly important in recent years as atmospheric pollutant levels have risen and land-use change has created problems with nitrate runoff and pesticide and sediment release.

The Institute has a wide range of water quality studies which address not only the problems of pollutant transport but also the development of models for forecasting and prediction purposes. These studies embrace projects concerned with acid rain and upland water quality, point source pollution in the lowlands, agricultural runoff and non-point source pollution. This research relates to problems both in the UK and overseas. IH also acts as the UK National Centre for acidification monitoring and modelling.

Upland water quality, acid rain and critical loads

Upland waters carry a chemical signature which is derived from the rocks and soils of the area. Over the past few decades, these pristine environments have been subjected to high levels of atmospheric deposition in the form of acidic oxides. These compounds have increased the acidity of stream water and soils which in turn have produced high levels of toxic aluminium and consequently severely damaged aquatic biota. Fish populations in many remote Scottish lochs have been destroyed.

Following recent comprehensive research programmes, the mechanisms by which water and soils are acidified and the links between hydrology and soil and water chemistry are now well understood. Also well understood are the links between the emissions of oxides of sulphur and nitrogen at point sources and their subsequent deposition over wide areas, often many hundreds of miles away. The establishment of this knowledge base has led to two important developments which may ameliorate the effects of acid deposition. These are the critical load concept and process-based mathematical models which are capable of predicting future stream chemistry responses.

The critical load concept assumes that there is a damage threshold for the response of ecosystems to acidic deposition which may vary for different receptors, such as soils or waters. The Institute has been at the forefront of such critical load calculation for UK surface waters and fulfils a vital role in managing and analysing data collected from a network of stream and lake sites which have been established to monitor the long term response of water chemistry to changes in pollutant deposition.

Measuring water quality in Nepal

Critical load maps for sulphur have been produced for the UK, based on present-day water chemistry and assumptions about the relationships with previous pristine conditions. They have one vital factor missing, however, and that is information on the time scale between emission reduction and ecosystem response. By incorporating our knowledge of catchment hydrochemical processes into a soil and water chemistry simulation model, the Institute took part in the development of MAGIC (Model of Acidification of Groundwater in Catchments) some years ago. MAGIC was developed and tested at IH in conjunction with co-workers at the University of Virginia and the Norwegian Institute for Water Research. It is based upon a lumped representation of the major processes controlling soil and water chemistry in catchments and it represents the only available technique for assessing the time dependence of critical loads. It is also able to quantify the importance of *not* achieving a desired critical load.

Future work will attempt to incorporate into the model a more explicit process basis for describing nitrogen dynamics in upland catchments. This will provide an invaluable tool for estimating nitrogen critical loads and the determination of emissions control policies for nitrogen oxides.

Water quality problems in the lowlands

A water quality module has been added to the IH Distributed Model (see page 26) to simulate the movement of nitrogen in soil and water systems. This research follows concern about nitrate concentrations in surface waters in some areas of the UK being above the EC limit of 50 $mg\ l^{-1}$ laid down in Directive 91/676/EEC. Changing farming practices should help to ameliorate this problem in the future but any such changes must be based on a sound scientific understanding of the qualitative link between agricultural practice and nitrate concentrations in surface waters.

The transport and transformation of nitrate in solution is being modelled at both the plot and catchment scales. Experimental and survey information on relevant parameters and variables is being collected from the 43 km^2 Bourne Brook catchment near Coventry, which provides water to Shustoke Reservoir, used for public supply. Nitrate concentrations in streamwater are monitored weekly at 12 sites, and cropping, fertilizer and related information is collected from farmers.

The fact that upland streams, already subjected to impacts from land-use change and atmospheric deposition, go on to become lowland rivers and then acquire further problems arising from duality of use, is a major concern for water resource managers. These difficulties have been approached within the Institute through the use of integrated catchment management models, a technique still in its infancy. Such models rely on the linkages between land use, population, pollutant input and water quality.

In developing countries the pressing need to produce food to sustain a rapidly increasing population has frequently led to a disregard for the natural environment and the consequences have been increased soil erosion, increased soil acidity, water pollution and loss of biological diversity. All of these act against the goal of increased productivity in the long term. Given the experience gained and models developed in the UK context, IH clearly has an important role to play in the development of management strategies for such countries to achieve sustainable development of natural resources.

Land-use change, sediment and water quality problems, Nepal

A unique opportunity to test available models and develop new model structures is being provided by a current programme of field research in catchments in the middle hills of Nepal. Run in conjunction with the Royal Geographical Society and His Majesty's Government, Nepal, this research programme focuses on the links between soil erosion, water quality and biological diversity, and agricultural practice. For example, high loads of mineral fertilizers are applied to rice terraces to force two crops per year. Much of this fertilizer finds its way into streams, increasing acidity and impacting on aquatic biota. Long-term application could lead to soil acidification, thereby limiting crop growth.

There exists a clear parallel here between the critical load concept applied in the uplands of the UK and the development of a technique for calculating a critical load for these agricultural areas. This would protect them against long-term environmental problems and provide for maximum efficiency in fertilizer application.

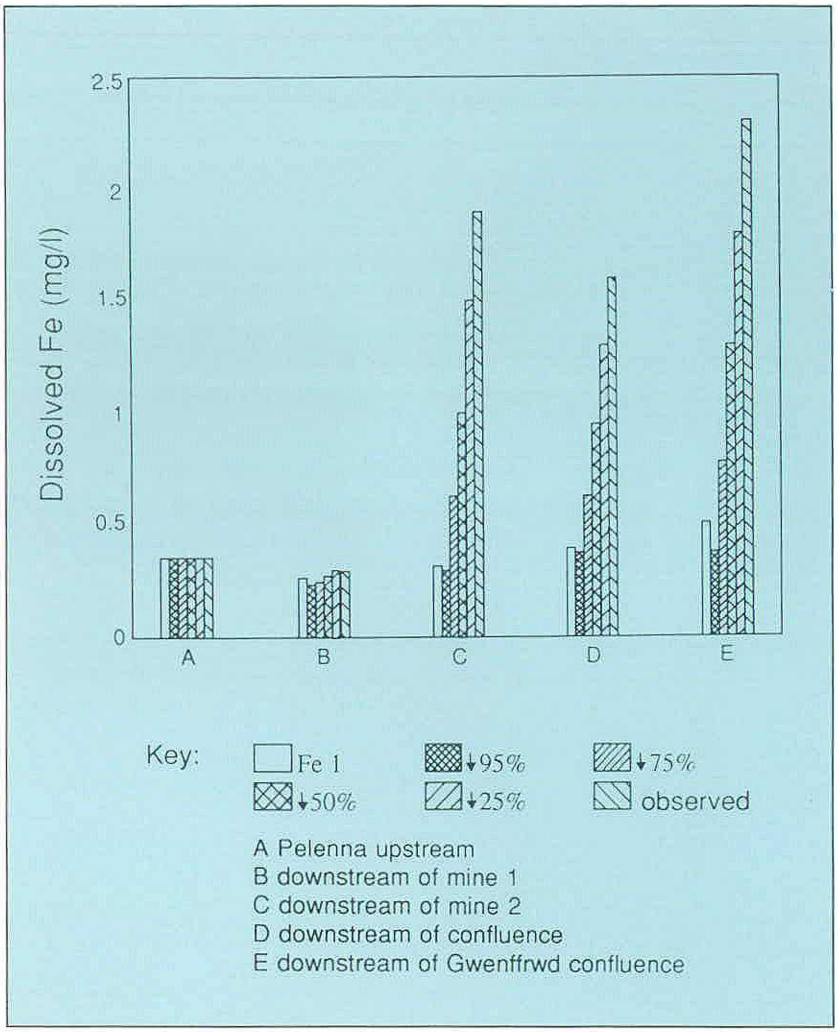


Figure 18 Modelled mean dissolved iron concentrations for the River Pelenna, South Wales. At each location, the bars show concentrations resulting from different model scenarios. Scenario Fe 1 involves a 95% reduction in iron concentration in the discharge from mine 2; the other four model scenarios express different percentage reductions of the iron concentrations in every mine discharge (including discharges joining the confluent River Gwenffrwd). The sixth bar shows the observed dissolved iron concentration.

Water quality models for environmental impact assessment

Mathematical models have a significant role in providing a systematic method of analysis within environmental impact studies. At IH water quality models such as QUASAR (QUAlity Simulation Along Rivers) have been used to assess the impact of the Roadford Reservoir on the River Tamar, the Maidenhead flood relief channel on the River Thames, and acid mine drainage on the River Pelenna in South Wales, for example.

In the case of the River Pelenna, the acidic, iron-rich discharges from disused mines have polluted the river significantly. Water samples taken by the NRA Welsh Region along the Pelenna and its tributary, the River Gwenffrwd, showed that concentrations of dissolved iron downstream of the mine discharges were above the limit for viable salmonid fisheries. Some lowering of the pH of the river water was also detected.

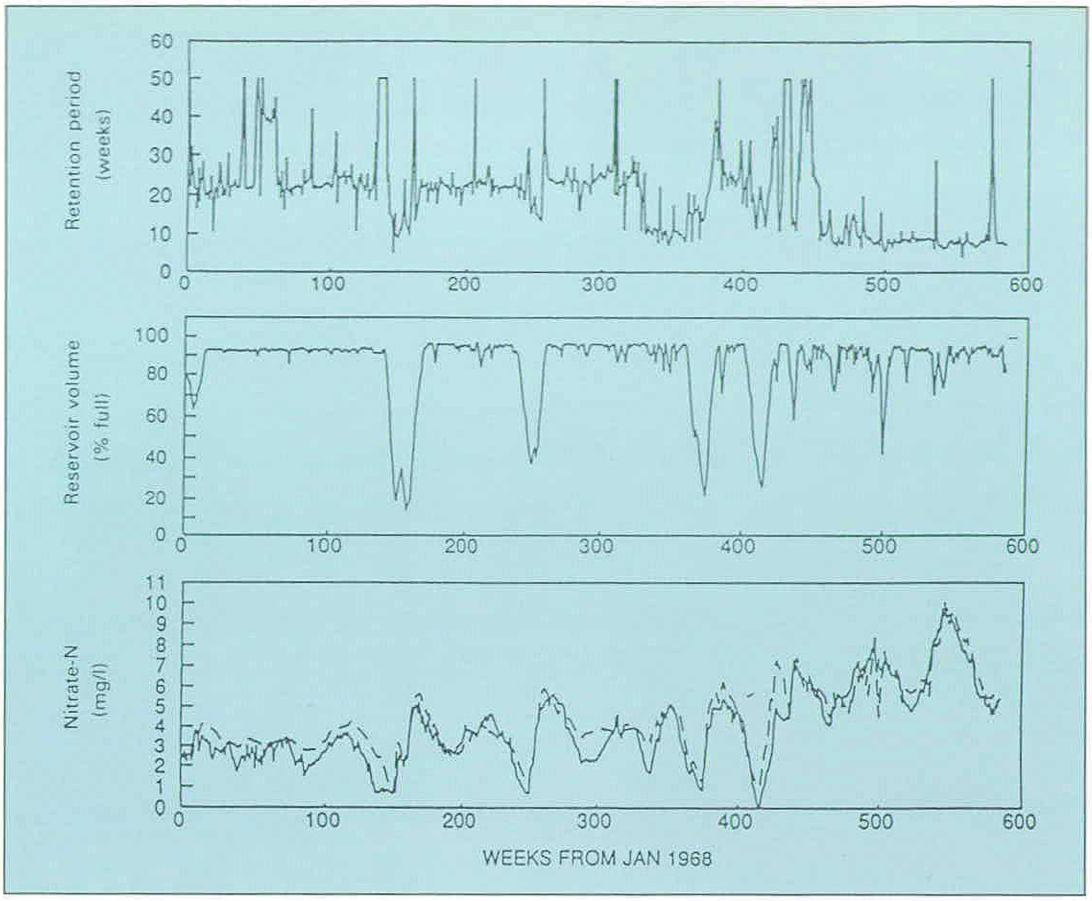


Figure 19 Nitrate, volume and retention period simulations for the Farmoor I Reservoir, Oxfordshire

The level of treatment required to allow salmon repopulation of the Pelenna and Gwenffrwd was determined with the QUASAR model. QUASAR was calibrated and run in planning mode for various scenarios of different degrees of treatment of the acid mine discharges (Figure 18).

A similar example is the development of a dynamic model of nitrogen in reservoirs. This model provides a mass balance over the reservoir and includes biological denitrification processes such that seasonal effects can be simulated. The 12 years of simulated and observed nitrate data for Farmoor Reservoir near Oxford presented in Figure 19 show that the model is particularly successfully at simulating seasonal and longer-term changes. Such models can be used either for planning purposes, to assess the impacts of increased nitrates from agricultural or atmospheric sources on reservoir quality, or for operational purposes, to assist in day-to-day management.

Water colour

Another area of concern with regard to water quality and environmental impact is that of water colour, as generated in upland peat-based catchments. Colour is produced by dissolved organic compounds which are derived from the bacterial decomposition of peat. Land-use change, such as moorland gripping and intense, low frequency heather burns, as well as the combination of dry summers and wet springs in much of the 1980s, exacerbated an endemic problem in upland water supplies.

Work carried out with the University of Leeds and funded by Yorkshire Water has focused on developing a simple conceptual model to estimate the colour response of Pennine water supply catchments. The model simulates the generation of colour during the summer drawdown of the water table. Colour is then released from the available store both by a slow release mechanism, dependent on the soil moisture, and by a more rapid release mechanism dependent on the rate of subsurface flow. The model parameters which control the rates of colour generation and release can be derived from the catchment characteristics of drainage density, the proportion of Winter Hill series peat and the residence time within reservoir storage. The model can be used, in either a forecasting or planning mode, to estimate future levels of colour, contingent on different weather scenarios.

Instrumentation: measuring hydrological processes

Hydrological research frequently requires simultaneous measurements of rainfall and streamflow together with precise and reliable information on water quality, soil water, or a wide range of other meteorological data. Although individual, essentially hand-held, instrumentation may be used in field survey, much modern research demands continuous recording from experiments lasting many days or even weeks. This requires a complete instrument system, usually automated, comprising a sensor (or more usually an array of sensors), interfaced to a logging unit. Instrumentation strategy at IH is to use commercial equipment whenever available and to adapt such equipment and develop system interfaces and software specifically for each experimental need.

Data capture - the heart of field experimentation

Central to the Institute's automatic data collection systems is the Campbell Scientific CR10 logger This will record data from comprehensive sensor arrays and can now be programmed to operate field instruments selectively. For example, stream samplers can be programmed to operate only after rainfall of a certain intensity, and then only while soil moisture content is above a certain threshold. With battery power and solar panel support, which has been tested from the Himalayas to African deserts and the Amazonian rain forest, the Institute has a sound, flexible field facility which can be focused on any hydrological data collection requirement, virtually anywhere in the world.

Good experimental practice requires periodic visits to check the equipment deployment. This provides the opportunity to retrieve stored data by transfer to small electronic modules for listing and processing in the laboratory. This operation now takes a matter of seconds and has proved to be extremely reliable, regardless of the location and weather conditions. However, on occasion it is desirable to telemeter data directly from the field. During the year seven IH Automatic Weather Stations used in the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS) were interfaced to a Space Technology (Oceanspace) data collection platform transmitter. Telemetry of hourly meteorological data is received at Wallingford and by three collaborating organisations in Brazil via the Meteosat satellite.

In this experiment the time slot for data transmission is set, and communication is one-way, from field to laboratory. In another experiment within the UK, the extensive Cellular Radio Network has been used to interface the CR10 logger, via a battery-powered modem, to a cellular telephone and pager. In the laboratory the modem and telephone, under PC software control, can now transfer data either automatically or on command. Two-way communication has also been developed which can, if necessary, modify the logger programme remotely to adjust the field experiment following analysis of earlier-transmitted data.

During the year the joint IH/RGS/Nepalese water quality study (see page 30) required a special development of equipment to protect their instruments from frequent lightning strikes which could interfere with their pH and conductivity measurements at remote Himalayan field sites. Rigorous earthing and a specially-developed interface between commercial sensors and the CR10 logger has allowed the successful deployment of a system storing hourly data of pH, conductivity, water temperature, stream level, turbidity and rainfall in one of the world's most demanding and inaccessible field locations.

Instrument engineering - big can be beautiful

The largest hydrological instruments are those which record river flow. Traditionally they comprise massive concrete structures, often built to very small tolerances and completely enclosing a stream or river. IH workshops have continued development of the use of aluminium for new streamflow structures and for the repair of existing concrete installations. Following a site survey, prefabricated aluminium modules built at Wallingford are dismantled and re-installed in the field. During 1991 a damaged concrete structure in our Plynlimon catchment was re-floored using this technique. An accuracy within 1 mm was achieved along the whole length of a major flume. This led to considerable savings in costs over the alternative rebuild option, while at the same time it allowed river flow records to continue, virtually without interruption.

The Surface Capacitance Insertion Probe (SCIP) on trial in Zimbabwe for irrigation control of sugar cane

Advances in soil moisture measurement - a new tool for hydrology

Since the 1960s IH has had an active R&D programme on instruments for the measurement of soil water content. For most of this period the neutron probe has been the preferred device: in spite of the radiation hazard and its unsuitability for automatic logging, alternative commercial instruments had not been developed. Dielectric constant has long been an attractive soil property for determination of its water content and the measurement of this forms the basis of the IH capacitance probe. A version designed and developed for use within an access tube, installed vertically in the soil, is already available commercially. It has better depth resolution and faster read-out than the neutron probe but it requires care in the access tube installation.

Neither this instrument nor the neutron probe is suitable for measuring the water content at the surface of the soil (the top 5 or 10 cm) and so a significant new development is the Surface Capacitance Insertion Probe (SCIP). This device is portable, lightweight, of relatively low cost, reads instantaneously and is simply inserted into the soil to make a measurement. Applications ranging from a rapid survey to mapping the soil moisture variability for use in irrigation scheduling are all being examined.

The SCIP development programme will include processing electronics to display soil water content directly and versions with data storage, as well as a low-cost basic unit. Automatic logging requirements have also been anticipated in its electronic and mechanical design concept. Field trials in the UK and abroad and extensive laboratory calibration and testing of ten prototype instruments has begun during the year. Patents have been obtained prior to full commercialisation of a major new hydrological tool.

IH developed and has operated Automatic Weather Stations for many years and is now extending the concept to Automatic Soil Water Stations (ASWS). A dedicated microprocessor controlled instrument for logging soil moisture data was first developed at the Institute for use with the neutron probe. It was subsequently developed further to accommodate the new access-tube version of the capacitance probe sensor. Essentially it was an electronic field notebook. Now, with the arrival of the Surface Capacitance Insertion Probe (SCIP), permanent installation on site is possible, and the CR10 logger has been modified to operate automatically at the core of a field station to monitor soil water content continuously.

The design is evolving through a number of different configurations built and tested within the IH research project programme. One of the most comprehensive has a raingauge and three spatially-separated arrays, each of which measures soil water content, tension and soil temperature. To date, development emphasis has been on surface measurements with sensors at 5, 10 and 15 cm depths; future programmes will extend this to 0.5 metres. In addition, the means and methods of sensor installation are an important part of the overall concept. Another planned development will include an automatic depth profiling sensor, using a modification of the access tube version. This ASWS opens the way to particularly exciting fundamental studies such as determining dynamically the water release characteristic as it is generated in the field by natural climatic events.

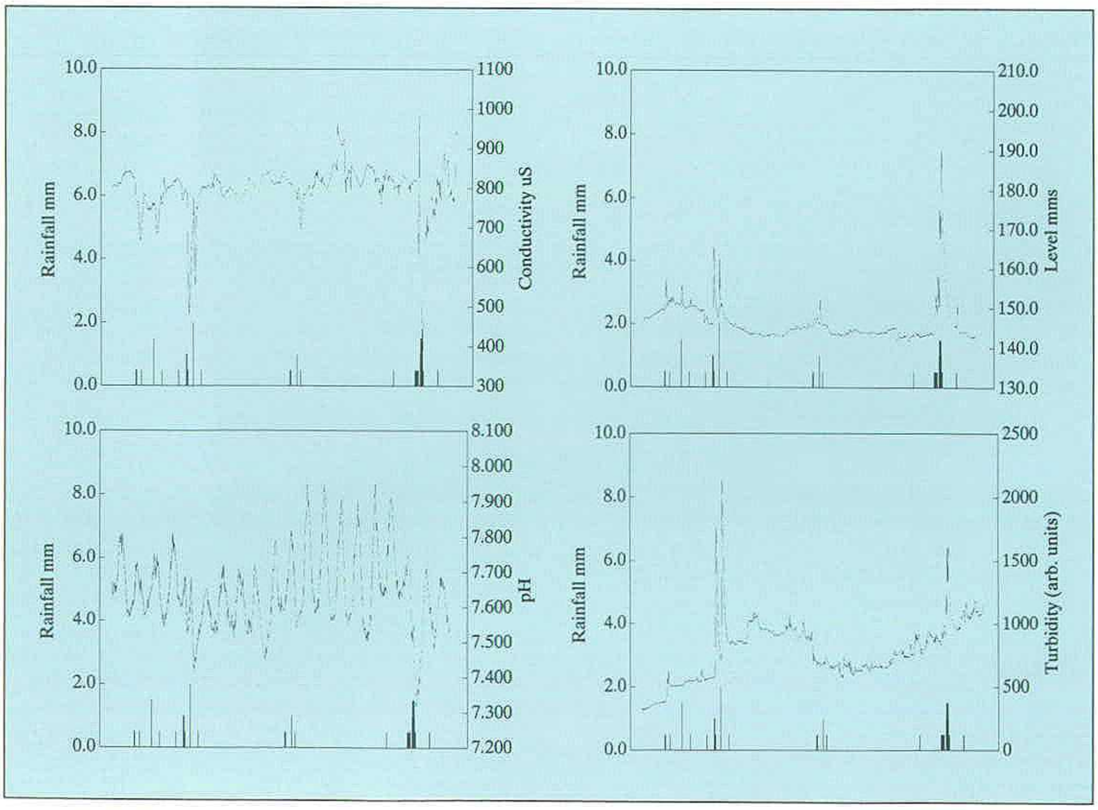


Figure 20 Water quality data for a 20-day period shown against rainfall. Changes triggered by the rain are clearly identifiable, as well as diurnal fluctuations in pH and conductivity.

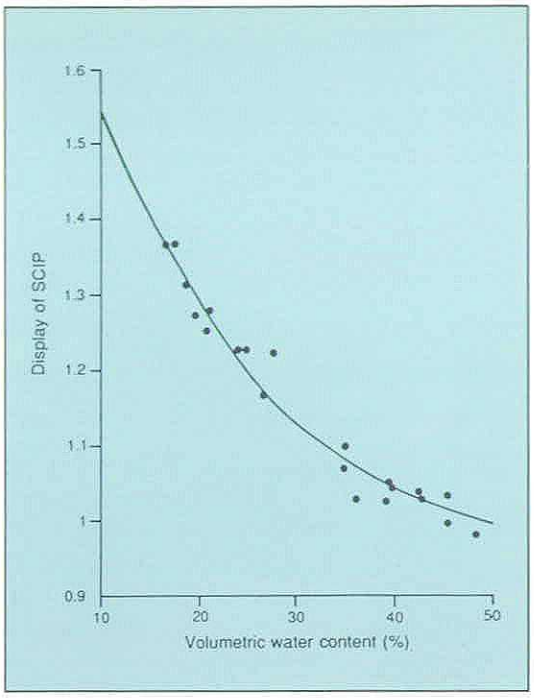


Figure 21 Typical sensor calibration of the surface capacitance insertion probe (SCIP). The points are field data with gravimetric analysis of samples centred on the position of the SCIP measurement. The curve is a theoretical model with two-parameter fit.

Direct measurement of evaporation — doing the impossible?

Evaporation determination has been fundamental to much of the Institute's field programme since its foundation. Initially, estimation techniques were reasonably accurate for short vegetation, plentifully supplied with water. Elsewhere considerable uncertainty surrounded experimental attempts to improve estimation techniques, and a direct measurement system, HYDRA, was developed by IH to research the problem. It is a compact, mast-mounted, multi-sensor array, interrogated by a dedicated microprocessor ten times a second to provide fluxes of heat and water vapour directly by eddy-correlation calculation. Nine experimental HYDRAs have been built and used for research from semi-arid savannah in Africa to tropical rain forest in South America.

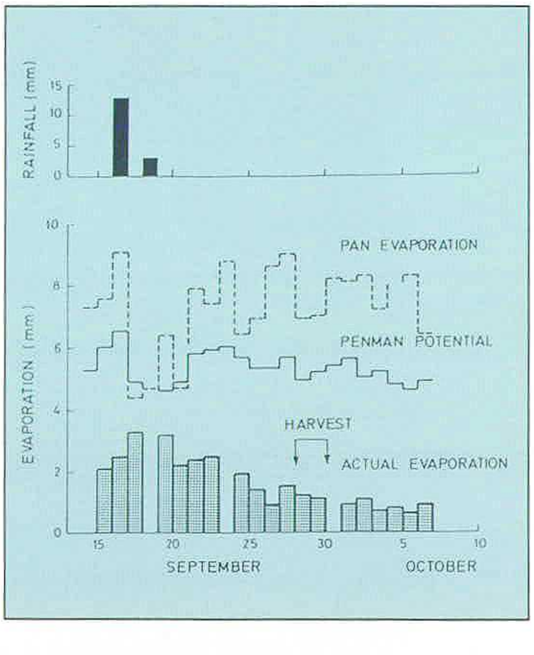


Figure 22 Actual evaporation measured by the HYDRA compared with the Penman estimate and pan evaporation.

Extensive use has led to improvements during the year in waterproofing. The instrument has also been made more robust without loss of aerodynamic profile. Electronic development has improved the stability of the infra-red hygrometer and shortcomings in the subsidiary commercial sensors monitoring the background humidity and net radiation have been rectified.

One series of development trials was combined with a study of evaporation from meadow land with shallow groundwater, just outside Oxford, potentially under threat from nearby gravel extraction. New quality control techniques were used on the data in order to supply a continuous record for calculation, with rainfall and soil moisture measurements, of an accurate water budget. Direct measurement showed that typically only *two-thirds* of the Penman estimate of evaporation actually occurred, emphasising that even with a shallow water table conventional estimation techniques of evaporation are often in considerable error.

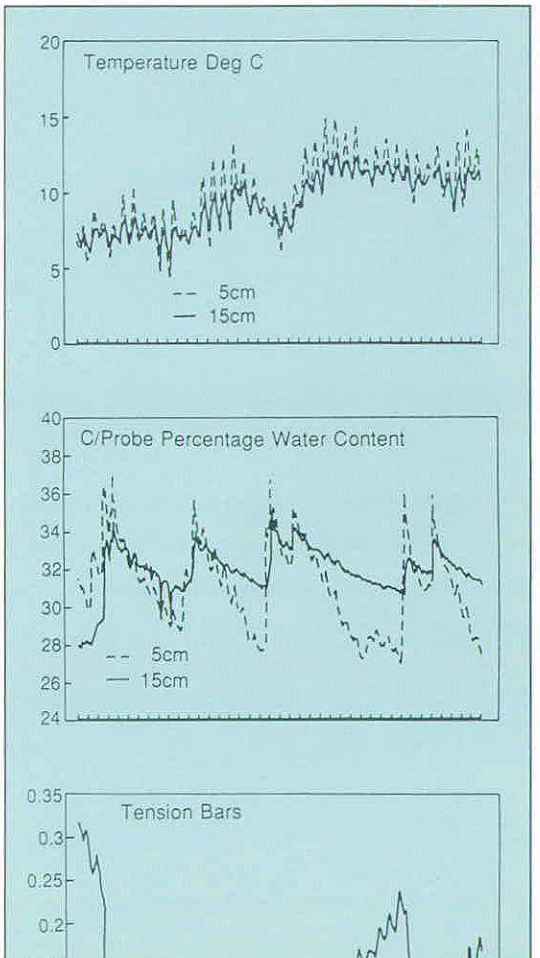


Figure 23 Temperature, capacitance probe measurements of water content and tension, measured hourly by the automatic soil water station, spring 1992. Diurnal fluctuations and a gradient with depth are apparent.

Reservoirs: saving for a non-rainy day

Reservoirs are frequently opposed before they are built, but once they have matured into the landscape they often become much loved. The United Kingdom has a rich heritage of dams, many dating from the industrial revolution. Although reservoirs in Britain primarily serve public water supply needs there are many with other functions, including hydro-power generation, flood control, canal maintenance, irrigation, power-station cooling, water sports, fishing and parkland amenity.

Every reservoir that stores over 25 megalitres requires a regular safety inspection by a qualified engineer on the appropriate panel overseen by the Department of the Environment. Some 2450 such dams are on enforcement authority registers. Of these, 535 exceed the internationally-accepted height threshold for a large dam, namely 15 metres. Within Europe only Spain, France and Italy fall into the same league as the UK.

A notable feature of UK dams is that they are mainly clay-fill structures. This makes the correct sizing of flood discharge arrangements particularly important, since the result of overtopping and consequent breaching of a dam would be truly catastrophic.

Reservoirs are constructed principally to retain wet season flows for use in drier times that lie ahead. The hydrologist is involved with many essential steps in reservoir development and use:

- identifying dam sites with good storage characteristics;
- assessing the water resource or "yield" available from alternative dam heights for a range of probabilities;
- maximising yield by augmenting inflows to the reservoir using catchment transfers, or by controlled releases to feed an abstraction point lower down the river;
- advising on expected sedimentation within the planned lake;
- assessing the flood risk to the construction programme;
- sizing flood spillway(s) and freeboard to control wave action;
- devising operating rules, often of a multi-objective nature, and proving their effectiveness by computer simulation;
- designing lake level and discharge instrumentation, often with associated raingauge and weather station equipment;
- interpreting gauged records to reassess water resource reliability, reservoir flood safety and to monitor water quality changes.

Energy-destroying drop structure on stream entering Semenyeh Reservoir, Malaysia

Refining techniques in all these areas is a regular part of the Institute's support to consulting engineers and dam owners both in Britain and abroad.

Besides balancing quantity, reservoir storage will average out the quality of the water in the various inflow sources. This means that a stream below an upland reservoir will rarely, if ever, return to the pristine quality of water in the natural stream before dam construction. The virtues of reservoir storage from the quality standpoint include:

- the trapping and settlement of the greater part of incoming sediment and turbidity loads, both organic and inorganic;
- the averaging of the temperature of abstracted water and of the chemical and bacteriological variability in incoming water;
- the decline of bacteriological counts with residence time;
- the dilution of occasional polluting inputs;
- the ability to choose water quality by selective operation of a multiple level drawoff.

The Institute has diverse research interests in reservoirs, new and old, and seeks to achieve a better understanding of their hydrological and environmental performance. Practical applications are now frequently supplied as software.

One such example from the past year was the installation, for SONEL, the Cameroun power authority, of a microcomputer package to determine optimum release efficiency from three large dams in the headwaters of the Sanaga River. The software includes HYRAIN, a system which displays rainfall measurements obtained via METEOSAT, and a version of the HYRROM package, a conceptual rainfall-runoff model, to translate the sub-catchment rainfall measurements and probability forecasts into expected flows at the hydro-power sites. The remainder of the package (provided by Power & Water Systems of Henley under the management of Lahmeyer of Germany) handles the reservoir system operation to optimise the hydro-electric plant operation.

A second example is the new Version 2 of the IH software package Micro-FSR. This executes the techniques of the Flood Studies Report (and its associated Supplementary Reports); it also embodies reservoir routing and the consequent iterative calculation of critical storm duration. The Construction Industry Research and Information Association's procedures for balancing pond design and sediment routing have also been incorporated into the new version, prior to their publication in the book *Flood Storage Ponds* which replaces CIRIA guide TN100.

Compensation flows in the UK

River flows immediately below dams in the UK are maintained by statutory compensation releases made by the reservoir operators to comply with the impounding licence and any associated Act of Parliament. Many of these releases may have originally been set with regard to industrial and political constraints which no longer apply. It was not until the end of the 19th Century that consideration was given to other water uses such as fisheries and effluent dilution. Since then nature conservation, recreation and the demands of existing licence holders have become increasingly important. Some flow regimes are now varied seasonally in conjunction with an agreed reservoir operating policy.

For some years the Institute has studied the quantitative and qualitative effects of compensation flows on flow regimes below reservoirs and has assessed their implications for aquatic ecology. This began with a review of release policies. As part of the study an archive of reservoir data was established for more than 500 reservoirs. Figure 24 illustrates the diversity of statutory compensation flows in comparison with the natural low flows at the same sites estimated using the IH Low Flow Studies methodology.

Reservoir storage reduces the magnitude and frequency of flood flows. Changes in the downstream flow regime are at a maximum immediately below the dam but may become insignificant 20 km downstream as the proportion of natural inflows from tributary sources increases.

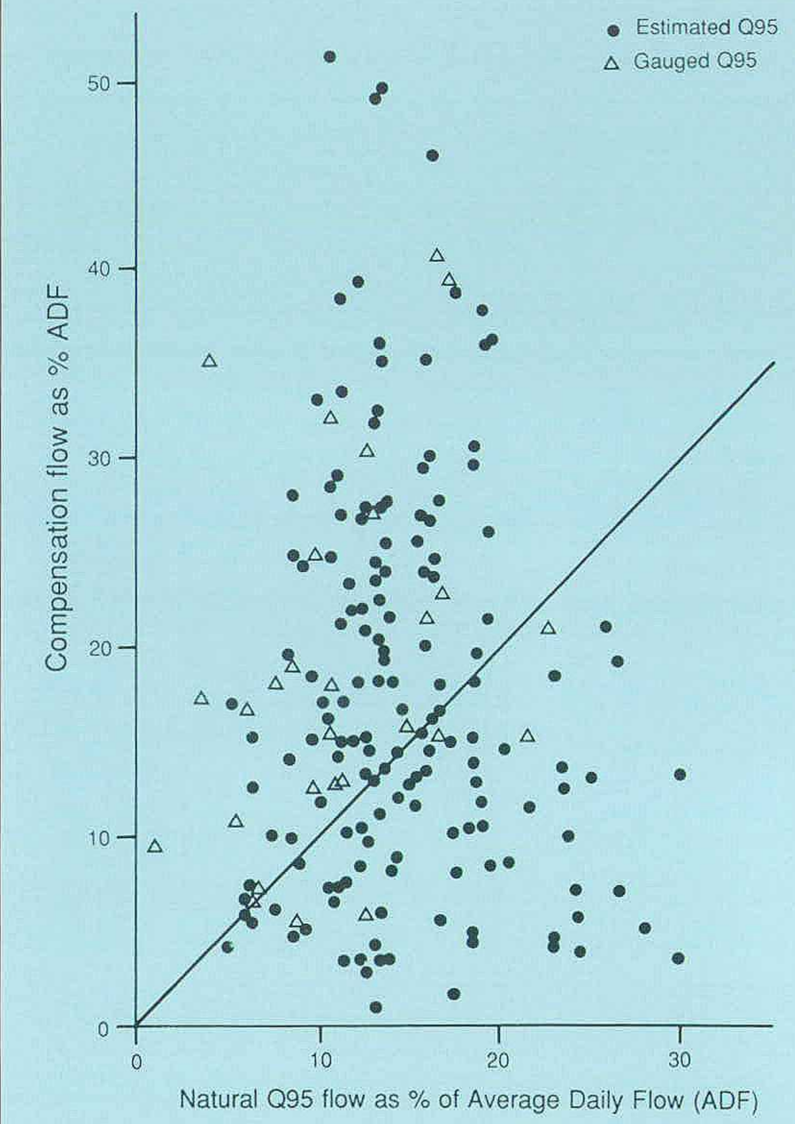


Figure 24 Relationship between UK reservoir compensation discharge and natural low flows for the same sites. Q95 is the flow exceeded for 95% of the time.

The ecological implications of changes in the flow regimes are being investigated using PHABSIM (Physical HABitat SIMulation) modelling. Different aquatic species, and even different life stages of the same species, may demonstrate preferences for particular physical habitat conditions, defined by depth, velocity, substrate and cover. PHABSIM relates discharge and habitat to the preferences of the life stages of a number of different target species so that ecological criteria may be used when setting compensation flows.

However there remains the essential conflict between in-river optimum conditions and any consumptive water abstractions of significant size. Figure 25 shows how the net yield (i.e. gross yield minus compensation flow) of a reservoir can vary with rules designed to protect a river more at one season of the year than at another.

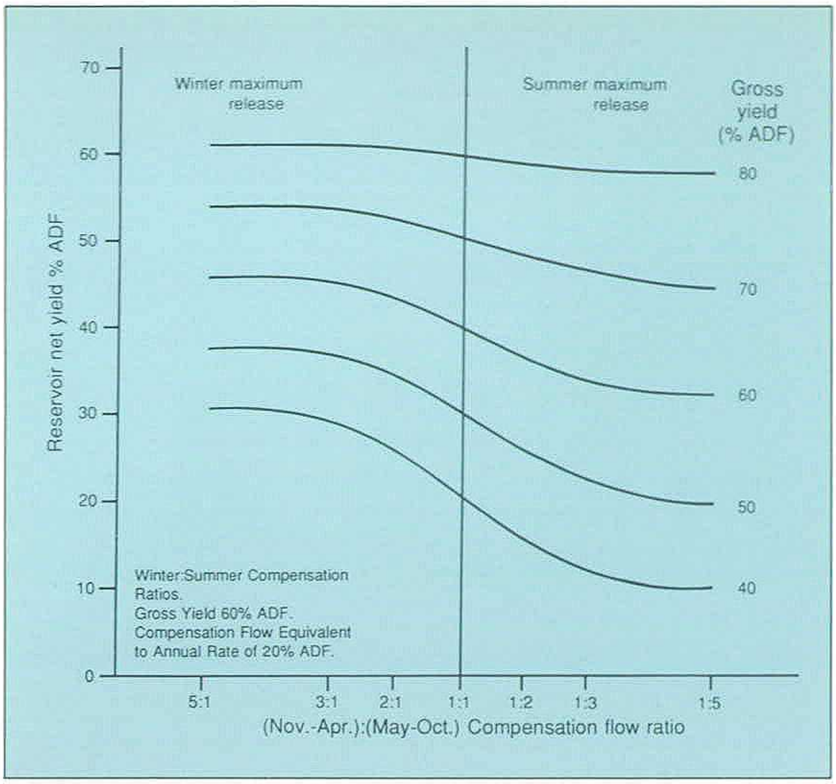


Figure 25 Relationship between net reservoir yield and seasonal compensation flow

Environmental extremes at reservoirs

The Institute carries out research on behalf of the Department of the Environment's Reservoir Research Committee and is assisting the Institution of Civil Engineers in its revision of the well known guide *Floods and Reservoir Safety*. European member countries of the International Commission on Large Dams were approached to identify the particular combinations of flood and freeboard standards in current use. Results were summarised in an IH paper presented to the 1992 British Dam Society Conference in Stirling.

For some years the trend has been for engineers responsible for dams to categorise the hazard that each poses to downstream communities. Ideally the risk of failure needs to be contained to a defined value, small but finite, and with recognition of its critical socio-economic importance. The UK practice since 1978 has been to choose a logical but arbitrary combination of events that must be handled. These are:

- a flood inflow of appropriate rarity (1 in 150/1000/10000 years or the Probable Maximum Flood)
- wave run-up from winds along the longest fetch to the dam (average annual maximum hourly wind or the 1-in-10-year hourly wind)
- reservoir just full or spilling its mean inflow.

The Institute is studying the combination of primary and secondary environmental variables that will cause a chosen rarity of water level against (or above) a dam crest. This advance in joint probability of environmental variables is a result of collaboration with the Department of Probability and Statistics at the University of Sheffield. Data from Eskdalemuir Observatory in the southern uplands of Scotland are being used to test the methodology. Twenty years (1970-89) of hourly data on rainfall, temperature (governing snow processes), wind speed and direction were provided from this site, which is representative of many reservoired valleys.

The schematic diagram in Figure 26 shows the elements involved and the need to take the input variability through both a catchment and reservoir model in order to understand the output variability. The statistical distribution fitted to the extremes of a particular variable is to be standardised in a Frechet form. The dependence between the extremes of those primary variables, although it may not be strong, is being tackled by point-process modelling. The secondary variables are treated as concomitants attached to the points defined by the primary variables with their conditional joint distributions being modelled.

As this theory matures, progress is being made separately on the simpler approach of trigger variables. Figure 27 shows how an index variable T can be defined to allow not only for storm rainfall R but also for weighted antecedent precipitation *API*. A range of such variables has been examined in the knowledge that seasonal soil moisture deficits have a profound effect on the risk of severe flooding in lowland England. This has now been quantified more completely than ever before by the completion of a peaks-over-threshold database of 77,000 UK floods during associated work for the Ministry of Agriculture, Fisheries and Food.

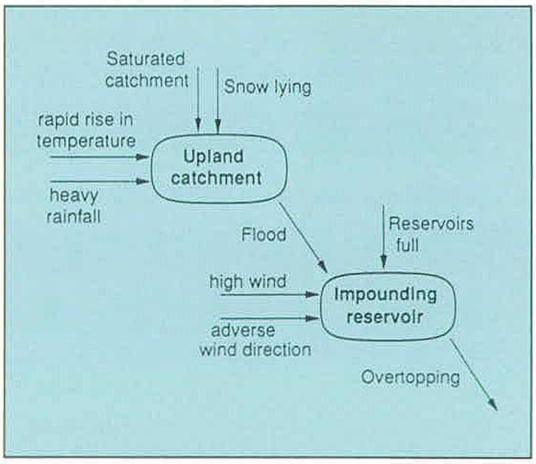


Figure 26 Environmental combinations of potential significance to dam safety

The past year has also seen the publication of IH Report 114 *Reservoir Flood Estimation: Another Look*. This shows that reservoired catchments are dramatically different to those from which conventional flood records are acquired by the national gauging network. Consequently there are risks in applying conventional Flood Studies Report procedures above dam sites. This report with its extensive comparisons of design floods for 15 reservoired catchments will be of particular value to the authorities responsible for reservoir safety.

Reservoir impact in Botswana

The Institute was commissioned (with Sir Alexander Gibb & Partners) to assess the cumulative impacts on basin resources of over 300 small dams that have been constructed in Botswana in the last 50 years. This southern African country of 570 000 km^2 includes the well-known wetland ecosystem of the Okavango delta. With an average annual rainfall typically in the range 250 mm to 600 mm and a seven-month dry season, storage is extremely important. The need is complicated by annual open water evaporation approaching 1900 mm.

Each dam has a different water balance and pattern of use. The Institute's HYDAM software has been developed to address the problem of each extra dam cutting off the catchment from storage downstream. Under its screen menu control, it is possible to zoom in on the region's digitised rivers to identify storage locations. The program's features include the ability to select an existing dam and to view the data held about it, or to select the location of a new dam and to enter data.

Using HYDAM it has become possible to simulate flows under three different conditions: the catchment before any farm dams had been built; with the dams which currently exist; and with the existing dams plus a range of dams which may be constructed in the future. The results showed that in some cases the water yields from the major reservoirs were considerably reduced by the farm dams, and that an increase in the number of dams would reduce the yields still further. The total capacity of small dams is the major factor which affects the downstream yields. Besides this, other minor factors were investigated and recommendations were made concerning the size, location and usage pattern of new farm dams in order to minimise adverse effects.

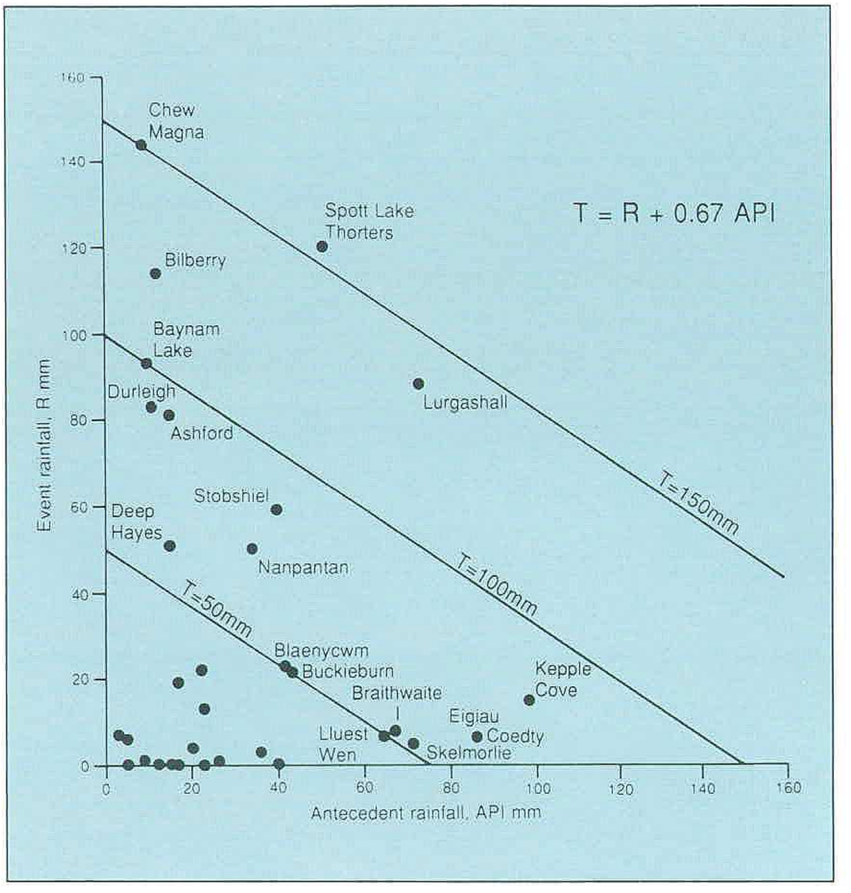


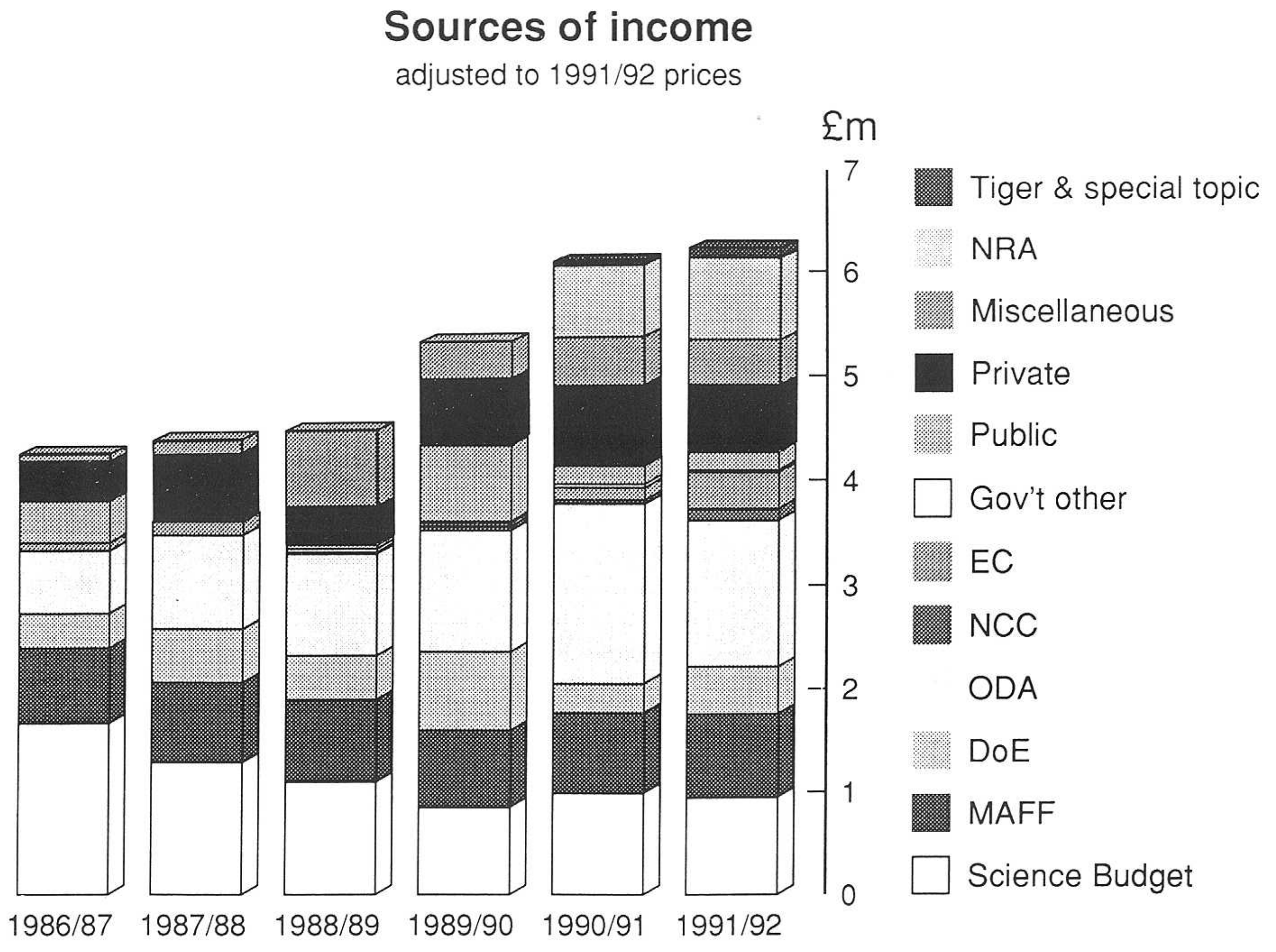
Figure 27 Event rainfall and antecedent rainfall for some UK dam safety incidents

Appendix 1 Finance

Sources of income

The histogram shows the Institute's income over the period 1986/87 to 1991/92 (adjusted to 1991 prices).

The Wallingford site is shared with staff working for other NERC Directorates, for whom the Institute receives Science Budget support to provide site services.



Appendix 2 Staff list as at 31 July 1992

Prof W. B. Wilkinson, PhD	Director	M A Plummer A. D. Spencer	Personal Secretaries
A.G P Debney, BSc	Assistant Director	S. A Phelan	Personal Secretary

HYDROLOGICAL PROCESSES

W J Shuttleworth, PhD
Divisional Head

B A Hawker
Personal Secretary

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

Vegetation and Sub-surface Processes
J. S. Wallace, PhD
- environmental physics
J. Bromley, PhD
- groundwater resources
J. M Roberts, PhD
- plant physiology; transpiration
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
A.-L C. McWilliam, PhD
- tropical vegetation gas exchange

Land Use and Water Efficiency
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
- fluvial sediment; quaternary geology
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
- microwave and thermal studies
K. Blyth, M Phil
- microwave remote sensing
J. W. Finch, PhD
- groundwater and GIS

ENVIRONMENTAL HYDROLOGY

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Divisional Head

J. A Champkin
Personal Secretary

Water Quality Systems
A. Jenkins, PhD
- hydrochemical modelling, acid deposition
A. Eatherall, BSc
- environmental modelling
W T. Sloan, BSc
- environmental modelling
C. A. L. Ishemo, BSc
- mathematical modelling
C. L. Shaw, MSc
- acid deposition
R J. Wilkinson
- modelling *E. coli* in streams
D. Butterfield
- assistant

Agrohydrology
C. H. Batchelor, PhD
- irrigation studies, crop water use
J. P Bell, BSc
- soil physics, pesticides: drip irrigation
C. M. K Gardner, PhD
- soil moisture studies
C. J. Lovell, PhD
- soil and water conservation
R J Williams, BSc
- water quality modelling
C. L Abbott, MSc
- agricultural water management
A. C. Johnson, PhD
- environmental microbiologist
P. C. R. Volkner, BA
- water quality catchment studies

Hydrological Modelling
R. J. Moore, MSc
- hydrological forecasting, weather radar, stochastic hydrology
D. A. Jones, PhD
- stochastic hydrology & forecasting
A F. 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
A F Chadwick, MSc
- hydrological forecasting
D. S. Hotchkiss, MPhil
- weather radar studies
D. R. Lewis, BSc
- 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
G. P. Ryland, MSc
- analytical chemistry
M. L. Harrow
- analytical chemistry

Experimental Catchments
J. A. Hudson, BSc
- nutrient & snow studies, catchment hydrology, hydrometeorology

Based at Plynlimon
K. Gilman, MA
- environmental impact, wetlands, mathematical techniques
G. J. L. Leeks, BSc
- 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 Balquhidder
R.C. Johnson, BSc
- catchment management, environmental impact

Hydrologic Geographical Information Systems
R. V. Moore, MSc
- digital mapping & information systems
D. G. Morris, BSc
- digital terrain models
N. J. Bonvoisin, BA
- WIS technical manager
C. D. Watts, MSc
- ICL Research Fellow
C. I. Tindall
- Water Information System trainer
R. W. Flavin
- consultant programmer

Flood Modelling
D. B. Boorman, PhD
- flood event modelling
M. Polarski, BSc
- catchment modelling
H. A. Houghton-Carr, MSc
- engineering hydrology
M. C. Clayton
- hydrologist
B. Gannon
- hydrologist

Flow Regimes and Environmental Management
A. Gustard, PhD
- regional resource studies
A. Bullock, PhD
- low flows
I. W. Johnson, PhD
- environmental management
A. J. Wesselink, Ir (*Wageningen*)
- European flow regimes
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
- consultant programmer

Flood and Storm Hazard
D. W. Reed, PhD
- applied hydrology
P. S. Naden, PhD
- basin modelling
D. C. W. Marshall, MSc
- engineering hydrology
S. M. Crooks, MSc
- engineering hydrology

E. J. Stewart, MSc
- rainfall studies; HYREX
I. J. Dwyer, MSc
- mathematician

Urban Hydrology
J. C. Packman, MSc
- urban hydrology
A. C. Bayliss, HND
- flood analysis; fieldwork supervisor

ENGINEERING HYDROLOGY

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Divisional Head

S. J. Beresford
Personal Secretary

Climate Change Impacts
N. W. Arnell, PhD
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N. S. Reynard, MSc
- hydrometeorologist

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. J. Bryant, BSc
- data acquisition controller; assistant editor
T. K. M. Jones, BSc
- hydrological data analysis'
S. C. Loader, BSc
- validation controller
R. E. MacRuairi, MSc
- database programmer
A. Matthews
- data validation; Visits Officer
S. Black
- National Water Archive office

APPLICATIONS RESEARCH, POLICY STUDIES & INFORMATION

A.G.P. Debney, BSc
Divisional Head

S. A. Phelan
Personal Secretary

Water Resource Systems
F. A. K. Farquharson, MSc
- overseas contracts, flood estimation
J. R. Blackie, MSc
- catchment studies, land-use change
R. B. Bradford, MSc
- groundwater resources management
J. R. Meigh, PhD
- water resources and flood estimation
N. R. Runnalls, MSc
- groundwater resources and alluvial aquifers
K. J. Sene, PhD
- hydrological modelling and evaporation estimation
M. P. McCartney, MSc
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V. J. Bronsdon
- hydrological assistant; cartographer

Hydrological impacts
B. S. Piper, MSc
- Head of Marketing; environmental impacts, water resource developments
M. C. Acreman, PhD
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A. J. Semple, BSc (Econ)
- environmental economist

Hydrology Software

Development
Y. P. Parks, MSc
- engineering hydrology and software development
K. B. Black
- systems analyst
K. Down, BSc
- software development
J. Zhang, PhD
- software development

Quality Assurance
J. R. Parker
- PC operations/software
G. N. Bell, BSc
- data processing and software sales

Instrumentation
T. J. Dean, PhD
- instrument development
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 and publications
J. H. Griffin, MPhil
- production editor
H. K. Stevens, BA
- production editor

Library
S. B. Wharton, BA
- librarian
D. S. Dolton
- library assistant

IAHS Press
P. J. Kisby
- manager
S. A. Cage
- assistant editor
P. J. Gash
- assistant

ADMINISTRATION

A. D. R. Gray
Head of Administration

Financial Management
H. M. Wood
- Finance Officer
A. M. Davies

Finance and Accounts
L. Aspinall, BSc
H. G. Thomas
C. J Allum
T. A. Gibson
L. Ross, BA
S. Walsh

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

Motor Transport
R. G. Drewett
- craftsman
H. V. R. Jones
- driver

Site Services
J. R. Fraser
- site services
J. Spencer
- caretaker/groundsman
I. R. Standbridge
- carpenter

Stores
J. H. Jones
- storekeeper

CASE STUDENTS

A. Black, BSc – St Andrews University
S. Evans, BSc – Nottingham University
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

SANDWICH COURSE STUDENTS

D. G. Aberg – Sunderland Polytechnic
E. J. Bent – Sunderland Polytechnic
L. C. Branham – Luton College of Higher Education
R. I. Burnill – Luton College of Higher Education
P. S. Cullimore – Coventry Polytechnic
S. K. Dawson – Luton College of Higher Education
J. A. Duckers – Sheffield Polytechnic
D. E. A. Elliott – Polytechnic South West
A. S. Fairhurst – Luton College of Higher Education
D. M. Hall – Coventry Polytechnic
N. J. Hasnip – Coventry Polytechnic
N. L. Mann – Luton College of Further Education
M. Marshall – Oxford Polytechnic
A. M. Odwell – Coventry Polytechnic
J. M. O'Hara – Coventry Polytechnic
J. Patel – Sheffield Polytechnic
F. M. Standley – Coventry Polytechnic
J. D. Sudlow – Coventry Polytechnic
S. Yaqoob – Brighton Polytechnic

COMMUNITY SCIENCE

TIGER (Terrestrial Initiative in Global Environmental Research)

Seconded from IH
M. A. Beran, BSc
- TIGER programme manager; TFS 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

Appendix 3 Publications

(i) Scientific papers

Acreman, M.C. 1991. The flood of July 25th 1983 on the Hermitage Water, Roxburghshire. *Scot. Geog. Mag.* **107**, 170-178.

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(iii) Software development

HYDATA version 3.1 Operation Manual, May 1992

Micro-FSR version 2.0 Operation Manual, April 1992.

Micro Low Flows version 1.3 Operation Manual, May 1992.

Appendix 4 Research projects

Programme 1 - Forest Science

Chemical and biological processes in forest soils

Programme 2 - Land Use, Agriculture and the Environment

Strathspey environment study

Programme 3 - Global Environmental Change

Mounting of FIFE data at Wallingford
Large-scale hydro-ecological modelling
Soil-vegetation-atmosphere transfer schemes – TIGER
Surface/boundary layer measurements, Sahel
Understanding SVATS for global modelling
Automatic weather station, Wytham site

Programme 4 - Management of Aquatic Ecosystems

Land-river interactions
Physical habitat simulations in rivers (PHABSIM)
Ecologically acceptable flows

Programme 5 - Impact of Man on the Hydrological Cycle

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
Hydrological studies, West Sedgemoor
Catchment urbanisation and flood runoff
Effects of agricultural soil erosion on watercourses
Runoff models for catchment planning
Updating the WURD database
Effects of the proposed A34 Newbury bypass

Catchment data
Plynlimon data processing, analysis & modelling

Hydrological modelling
Physically based modelling, the IH Distributed Model
Système Hydrologique Européen (SHE) Model
Real-time forecasting of river flows
Distributed hydrological & hydrochemical models
Weather radar and climatic hazards
Yorkshire river flow forecasting system
Regional & national radar rainfall forecasting
Variations in storm rainfall over London
Modelling nitrate leaching to surface waters
Weather radar and storm & flood hazard
White Cart flood forecasting system
River flow forecasting system training programme
Distributed flood forecasting models
Anglian flow modelling system

Water quality
European network of catchments study
Water quality modelling design & management
Pesticide pollution in catchments
Acid waters monitoring network
Balquhidder water quality study
Water colour modelling
Organics in the aquatic environment
Modelling the effects of climate change
Critical loads of sulphur and nitrogen
Modelling recovery from acidification
Nepal research project
Middle Thames: water quality modelling
Nepal regional water quality survey
Modelling *E. coli* concentrations in streams
Bursa environment programme, Turkey
Acid mine modelling

Agrohydrology
Mauritius drip irrigation: special studies
Small-scale irrigation schemes: collector wells
Soil physics drip irrigation: special studies
Estimation of effective rainfall
Management of limited water resources
Low-cost, high-efficiency irrigation
Pollutant transport in soils and rocks

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

Consultancy, UK
Minor repayment studies
Sub-surface exploration contracts
Cransley Lodge hydrological monitoring study
Editorial services: WMO Dublin conference
Flood frequency estimation, River Tinney
River Roding fluvial/tidal flood study
Joint training activities with HR Wallingford Limited

Consultancy, Overseas
Future water supply strategy, APC Jordan
Support services for overseas repayment studies
Evaporation study for Okavango swamp, Botswana
Upper Chi development, feasibility study
Komati basin, Swaziland
Real-time flood forecasting - Hong Kong
North Yemen water resources master plan
Bhola II feasibility study, Bangladesh
Training in flood forecasting for Bangladeshis
Flood analysis, Cul-de-Sac Valley, St Lucia
Spring-water survey, State of Qatar
Yemen water resources study
Hydrological research proposals
Impact of small dams in Botswana

Programme 6 - Land Surface Water Balance

Land surface energy balance
First ISLSCP Field Experiment (FIFE)
Hydrological atmospheric pilot experiment (HAPEX)
Energy balance of Sahelian savannah

Modelling regional scale evaporation, Sahel
Regional scale surface energy balance
UK Meteorological Office joint development (MITRE)
Boundary layer development in the Sahel
International desertification experiment

Vegetation water use
Plant physiological controls of evaporation
Water use efficiency of rainfed crops
Broadleaf plantation in lowland Britain
Sahel water balance conference
Water use by vegetation in the Sahel

Environmental impact of trees
Environmental implications of trees and land-use systems
Western Ghats forest project, India
Impact of eucalyptus plantations in Portugal

Sub-surface processes
Hydrology of shallow groundwater environments
Measurement of soil hydraulic properties
Worton Rectory Farm groundwater investigation
Arid zone recharge
Groundwater storage in chalk aquifers
Hillslope processes: Zimbabwe
Impact of flood protection on wildlife habitats
HAPEX II - Sahel: soils
Groundwater modelling of Thorne National Nature Reserve

Physics of surface/near surface hydrological models
Stream hydrograph and storm runoff mechanisms
Monitoring of soil moisture for flood hydrology
Monitoring and modelling of raised mires
Continuous monitoring of soil moisture for the NRA

Remote Sensing
Remote sensing of semi-arid regions
European Space Agency ERS-1 mission
Application of remote sensing to hydrology
Remote sensing for hydrological models
ERS-1: microwave remote sensing in hydrology
Evaporation input for GCMs from satellite data
Review of remote sensing techniques
PC-based system to use satellite data
Mapping of riparian vegetation, Upper Thames

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

Programme 7 - Environmental Pollution

Environmental assessment — Taiwan

Programme 12 - Atmospheric Science & Hydrological Extremes

Surface Water Archive
UK surface water data
Water resources research progress
The 1989/90 Yorkshire drought
Modelling multiple wet season floods

Flood event modelling
Flood hydrograph estimation procedures
Representative basin database

Flow regimes
Flow regimes in Western Europe
Micro low flows
Land use and water resources in Southern Africa
Broad Oak reservoir hydrology
Low flow estimation in artificially influenced catchments
Low flow estimation in the Philippines
Modelling faunal and floral response
European small hydropower atlas
UK low flow training course

Storm hazards and hydrological extremes
Small catchment response, radar/water levels
Review of flood studies, statistical procedures
Rainfall extremes
Acute rainfall variations in upland areas
Flood estimation methods: training courses
Asian/Pacific tropical flow regimes
Rainfall forecasts, Cameroon hydroelectric schemes
Joint probability study (reservoir safety)
Allowance for Discretization in Hydrological and Environmental Risk Estimation (ADHERE)
Rainfall frequency study: England and Wales
Bank-full return periods for Thames weirs
Rainfall-induced landslides

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

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

Programme 13 - Scientific Services

Hydrological instrumentation
Capacitance probe
Automatic weather station
Field instruments
Maintenance and development of Hydra equipment
Soil laboratory
Influence of soil type on capacitance probe calibration

Information and dissemination activities

Hydrochemistry laboratory

Appendix 5 Wallingford meteorological station: 1991 summary

The meteorological station maintained by the Institute of Hydrology has been in operation since 1962. It is a recognised climatological station reporting to the UK Meteorological Office, Bracknell. Its location is at National Grid Reference SU 618 898 at an altitude of 48 m above Ordnance Datum. Contemporary and long-term data from the site are used in hydrological monitoring programmes and to support a range of research work.

Despite below average sunshine for the year, 1991 was marginally warmer than average, although the average temperature was well below the record levels of 1989 and 1990. Rainfall was below average for the fifth successive year, and the five-month period beginning in August was the third driest such sequence in the Wallingford record. The December rainfall total was exceptionally low, heralding the driest winter in the entire thirty-year record.

Month	Mean air temperature °C				Total rainfall mm			Days with rain	Total sunshine hours		
	1991	29y *	max	min	1991	29y *	% *		1991	29y *	% *
Jan	3.6	3.7	6.5	0.7	72.4	50.8	143	16	61.3	47.7	129
Feb	1.2	3.7	4.9	-2.6	26.1	34.5	76	11	57.2	67.8	84
March	8.0	5.8	11.9	4.0	36.8	44.8	82	14	81.2	106.2	76
April	8.0	7.9	12.4	3.5	61.3	39.6	155	14	127.3	145.9	87
May	10.7	11.2	15.3	6.1	9.6	50.7	19	8	122.7	183.0	67
June	12.6	14.2	16.9	8.2	67.3	51.5	131	22	120.1	187.9	64
July	17.7	16.3	22.6	12.7	75.6	42.1	180	13	189.5	186.8	101
Aug	17.5	16.0	23.3	11.7	18.1	55.3	33	6	218.0	175.1	125
Sept	14.9	13.7	20.6	9.2	50.4	48.9	103	11	162.7	138.2	118
Oct	10.1	10.7	13.7	6.4	39.5	51.4	77	12	75.1	98.7	76
Nov	7.2	6.5	10.3	4.0	57.2	52.6	109	12	57.2	63.0	91
Dec	4.1	4.5	7.7	0.5	11.3	57.5	20	7	49.4	37.4	132
YEAR	9.6	9.5	13.8	5.4	525.6	579.6	91	146	1321.7	1437.6	92

* 29 y is the 29-year monthly mean; % is the 1991 figure as a percentage of the 29-year mean.

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