Major hydrological events - a roller-coaster year

The very unusual weather patterns which have characterised much of the post-1987 period in the United Kingdom achieved an extreme expression in 1990 when parts of lowland England registered their second driest year this century whilst Scotland experienced its wettest year in a series from 1869. The remarkable hydrological conditions stimulated considerable scientific and public interest.

Much attention focused on the degree to which persistent drought conditions posed a threat to the aquatic environment, and to water resources in the English lowlands especially. However, notable flooding was widespread early in 1990 and the greatly accentuated seasonal variations in rates of runoff and groundwater recharge over the year ending in the late summer served to highlight similarities between conditions in 1989/90 and an emerging consensus regarding the possible impact of climate change in the United Kingdom.

Flooding near Dalguise (Tayside), February 1990
Photo: Scot Rail, Area Civil Engineer Perth.

Crue près de Dalguise (Tayside), Février 1990

Given the capricious nature of our climate and the already pervasive impact of man's activities on hydrological systems, the detection of any, initially faint, trend from the general variability remains a major scientific challenge. Nonetheless, the impact of weather conditions over the 1989/90 period may provide important insights regarding our vulnerability to climate change.

In response to an intensifying drought over the winter of 1988/89 in southern Britain, the Department of the Environment requested IH (which maintains the National Surface Water Archive) and the British Geological Survey (which maintains the National Archive of Groundwater Levels - also at Wallingford) to re-activate a nationwide hydrological monitoring programme. Data held on these archives provide the essential historical perspective against which to examine the current volatile episode.

For Great Britain as a whole, the 1980s was the wettest decade on record and until late-1988 provided little forewarning of the erratic conditions to come. A notable spring/summer drought afflicted western and northern Britain in 1984 but much of the concern generated by the Great Drought of 1976 was dissipated over the ensuing dozen years. Any complacency was rapidly dispelled in 1989 however when a very dry summer - following an extended period of rainfall deficiency - intensified drought conditions across much of eastern Britain.

Fernworthy Reservoir (Devon), September 1990
Photo: Geoff Loader

Le réservoir de Fernworthy (Devon), September 1990

High temperatures encouraged record evaporative demands, and soils remained exceptionally dry throughout the autumn in most eastern lowland areas. As a consequence the normal seasonal recovery in runoff and recharge was greatly delayed. By December groundwater levels in the Chalk were remarkably depressed; at Chilgrove, in the South Downs, the water-table declined to its lowest winter level in a 154-year record and the water resources outlook was very fragile throughout much of the English lowlands.

Heavy and widespread rainfall from mid-December helped to change the complexion of the drought and the transformation continued into 1990. Precipitation amounts were especially notable in Scotland - rainfall over the January-March period was easily the wettest for any three-month accumulation in the Scottish rainfall series. Sustained rainfall early in February - associated with a moist, warm south-westerly airstream - induced a rapid thaw on windward slopes triggering notable flood events throughout much of the country; snowmelt made a major contribution to many late-winter flood events in northern Britain.

On the 4th February the River Tay - the UK's largest river in discharge terms - registered a daily mean flow (at Ballathie) of 1647 m^3s^{-1}, exceeding the previous highest daily flow rate held in the Surface Water Archive. Widespread flooding resulted in massive disruption of road and rail transport and substantial damage to agricultural land. Rivers were also in spate throughout most of England and Wales and the

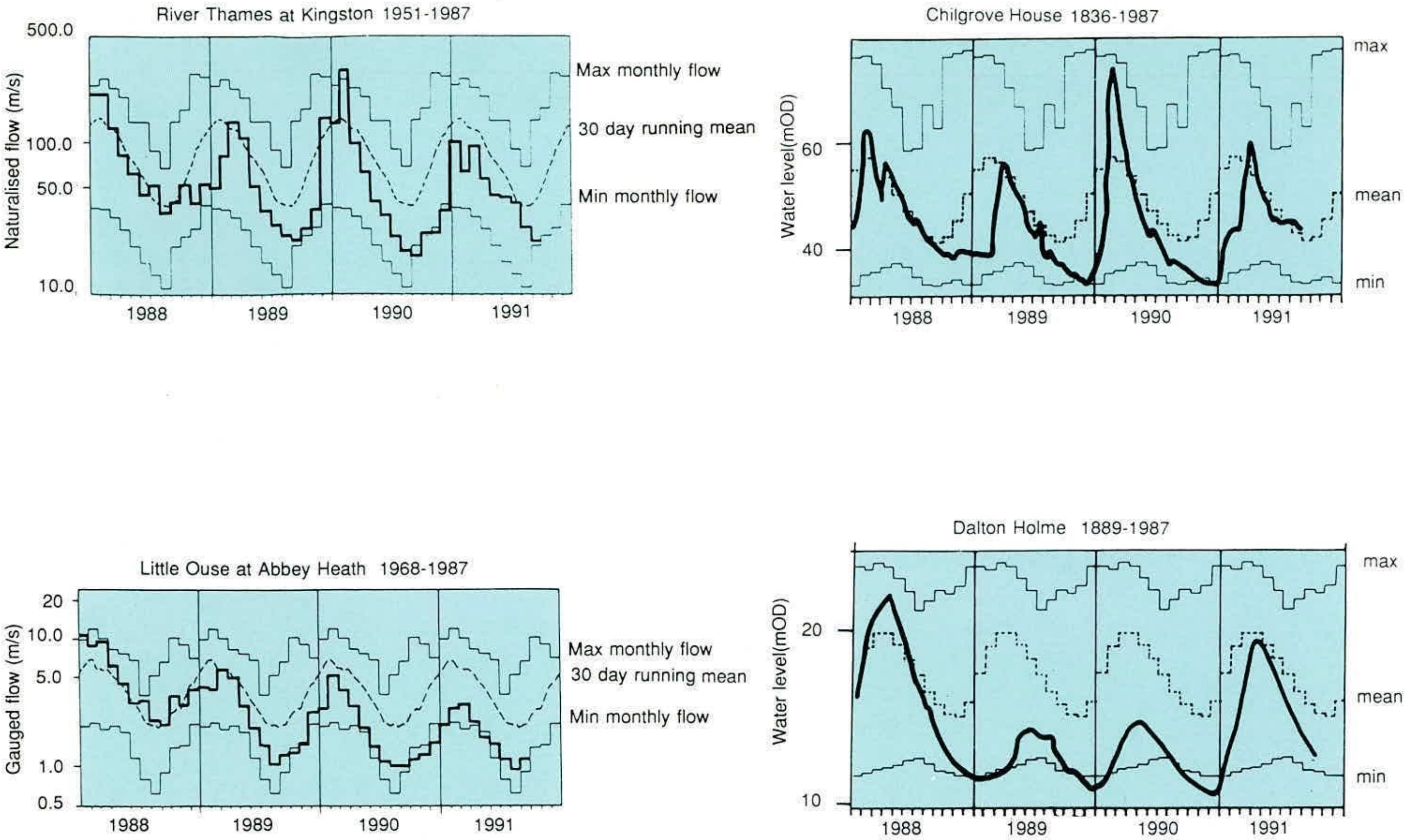


Figure 1 River flows and groundwater levels, 1988-91

Débits et niveaux piézométriques, entre 1988 et 1990

total freshwater outflow from mainland Britain in February 1990 was the highest for any month in at least 30 years.

The wettest winter (December-February) on record was generally welcomed by water managers but the heavy rainfall following extended drought conditions produced a number of water quality problems. In parts of the English lowlands, very high nitrate concentrations prevented the abundant runoff being capitalised upon to replenish some pumped storage reservoirs. A number of game-fish mortalities in western moorland streams were also attributed to increased acidity associated with the sustained heavy rainfall.

An exceptionally dry spring then produced a further plunge on what was becoming a hydrological rollercoaster ride. The driest March-May period in England and Wales since 1893 served to underline the particular importance of spring rainfall in relation to water resources. Most reservoirs in the west were at, or close to, capacity by the end of January; many smaller impoundments could have been filled again over the ensuing three weeks and, in Wales especially, controlled releases were necessary to provide a measure of flood alleviation storage. The benefit of notably high winter runoff was, however, counteracted by the very early onset of the seasonal drawdown as demand exceeded replenishment.

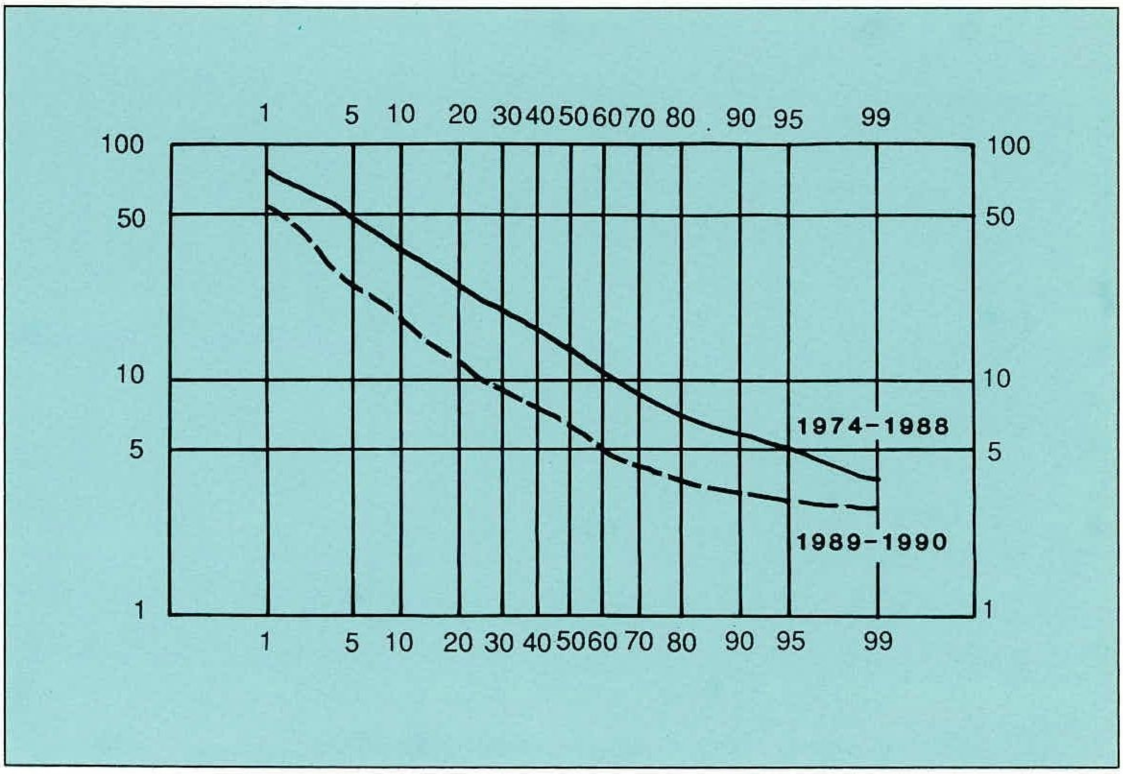
Whilst the summer of 1990 was not exceptionally dry, the warm conditions, high evaporation rates and parched soils, contributed to a steady intensification of the drought. By late-September, a severe seven-month drought extended across much of southern Britain. For England and Wales as a whole, the March to September period was the driest (for that period) in a general rainfall series beginning in 1767. Many eastern rivers experienced depressed summer and autumn flows for the third successive year and flow patterns over 1989/90 often contrasted sharply with those which characterise the preceding record. Whilst the range of recorded flow variation was extended in 1990 in a number of western rivers the period since the summer of 1988 has seen low flow statistics largely redefined in parts of the English lowlands.

Hot sunny conditions throughout the extended summer of 1990 stimulated increased demand for water (especially for gardens) and triggered measures to restrict usage - mostly hose-pipe bans. Whilst in terms of public perception the drought assumed a high profile principally in the summer, the hydrological character of the drought reflected the warm conditions - and associated high evaporation rates - throughout the year. Mean temperatures and total sunshine hours for 1990 eclipsed the records established in 1989 and potential evaporation losses were remarkably high. The high water temperatures and low dissolved oxygen content of streams caused stress to fish and the recreational use of some reservoirs was temporarily curtailed as a result of algal blooms.

By late November 1990, many spring-fed

Figure 2 A comparison of flow duration curves for the River Derwent, 1974-88 and 1989-90

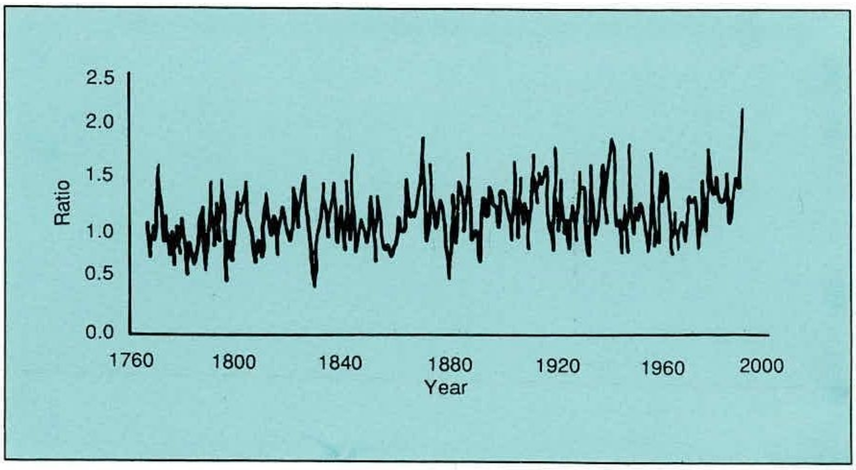
Une comparaison de courbes de durée pour le Derwent de 1974 à 1988 et de 1989 à 1990



streams, and a large number of ponds, had remained dry for several months - the loss of amenity for extended periods since early 1988 had been considerable and was accompanied by a substantial, if temporary, loss of habitat for fish and other aquatic life. The shrinkage of drainage networks was exacerbated in some, mostly eastern, areas by the impact of heavy groundwater abstraction on river flows. Generally the reduction in runoff, which is particularly evident in the headwaters, reflects long term increases in groundwater pumping often extending over 40 years or more.

Figure 3 The ratio of winter to summer half-year rainfall for England and Wales

Le rapport de pluviométrie hiver-été pour l'Angleterre et le Pays de Galles



However, for much of the post-1976 period, the effects have been disguised - or ameliorated - by the preponderance of relatively wet winters.

In many lowland areas the late-September soil moisture deficits were the equivalent of more than two months of average rainfall. Given the dry autumn in the east, one important effect was to, again, greatly delay the onset of infiltration. As parts of the Thames Valley experienced their tenth successive month with below average rainfall, early December flows in the River Thames fell short of those registered a year previously. Only in 1901 have appreciably lower discharge rates been recorded at the beginning of winter. In water resources terms the outlook was least encouraging in the East Midlands, East Anglia and the South-East where the 1990 drought overlay a substantial long term rainfall deficiency - entering the 1990/91 winter, some districts had recorded only four or five months with above average rainfall since the spring of 1988.

Widespread blizzards in the second week of December heralded a further change in weather conditions. A series of active depressions on a mild south-westerly airflow brought substantial rainfall to all areas and generally produced a transformation in river flows reminiscent of, but less dramatic than, that witnessed a year earlier. The water resources outlook improved considerably by the year-end and aquatic habitats began to take on a more familiar appearance. Nonetheless, in parts of the lowlands - especially in a zone extending from Kent to Lincolnshire - the drought continued to intensify and water-tables remained at, or close to, period of record minima heralding a continuation of the groundwater drought through 1991.

From deserts to rainforests - hydrological research in the tropics

The seemingly inexorable growth in human populations is concentrated in the tropics, and this provides a focus for research into its hydrological consequences. The primary impact is at the local scale, as individual farmers or communities face the need to provide food and potable water, or as industry grows and environments are changed in consequence.

Since they have common cause, these changes acquire consistency at the regional scale and the individual effects can conspire and interfere, such that there is a broader hydrological consequence in soils and rivers or in the atmosphere. Indeed, present and future changes to the way we use land surfaces are now large enough to influence the water cycle of the earth itself, with interactions between different regions via the atmosphere and the river systems which link them.

The Institute's research in tropical regions circles the globe. It is a balance of strategic and applied study of globally-relevant issues, ranging from the impact of tropical deforestation and dryland degradation to satisfying immediate needs, such as the provision of water, food and fuel wood, both at the regional scale and for individual communities.

The fragile Sahel

Water is at its most valuable when in short supply, and the arid and semi-arid regions have the world's most finely balanced hydrological systems. In such areas with erratic and sparse rainfall, groundwater is often the sole source of perennial water supply and its sustainability depends on recharge to the aquifer system. This recharge is small in quantity, and erratic in both space and time.

Quantifying this resource is a major challenge, one that is being addressed through the SAGRE project (Semi-Arid Groundwater Recharge Experiment). This project is being carried out in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at the Sahelian Centre in Niger, but seeks to provide an understanding relevant to the whole African continent and beyond.

Tiger bush is one of the important natural vegetation covers in the Sahel. As its name suggests, it is made up of dense bush and bare soil in alternative strips, typically tens of metres across. Early results from SAGRE in Figure 4 show the very different recharge beneath these two, and illustrate the difficulty involved in measuring the areal average recharge rate.

Nowadays, deep wells can provide ready access to subterranean water and, in consequence, grazing animals can be watered over extensive areas. This may result in overgrazing, and the loss of vegetation cover which, together with the enhanced removal of firewood, exposes large areas of bare soil. Unprotected from the aggressive tropical rains, these soils can form crusts, reducing infiltration and groundwater recharge, and enhancing runoff and soil erosion. There is some evidence that such changes in the land cover, when extended to a whole region, may generate a positive feedback in the atmosphere above, tending to reduce rainfall and to exacerbate the desertification process.

Investigation of this possible feedback has been the major objective of the SEBEX project (Sahelian Energy Balance Experiment). It has clearly shown that adjacent areas of ungrazed savannah and bare soil, the extreme limits in the degradation process, do indeed return very different amounts of water to the atmosphere (see Figure 5).

The SEBEX study has now grown into a major new international experiment, to be called the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel). Starting in 1992, IH researchers will work alongside additional NERC-supported scientists from the UK and with co-workers from Niger, France, the Netherlands, Germany and the USA to carry out a coordinated study of a 10,000 km square region around Niamey in Niger. The research involves extensive ground-based measurements concentrated at three main sites, these being overflown by boundary layer sounding aircraft and satellite measuring systems (see Figure 6).

Water and crops

Notwithstanding the requirement to understand these atmospheric feedbacks, there remains the imperative to mitigate the pressures which drive the dryland degradation process itself, chief amongst these being the need for food and firewood. Efficient 'garden' irrigation schemes, which exploit limited groundwater resources with maximum efficiency and with minimum risk

Tree stumps still smouldering after typical rainforest clearance in Amazonia, Brazil

Souches couvant sous la cendre après le défrichement de la forêt tropicale en Amazonie, au Brézil

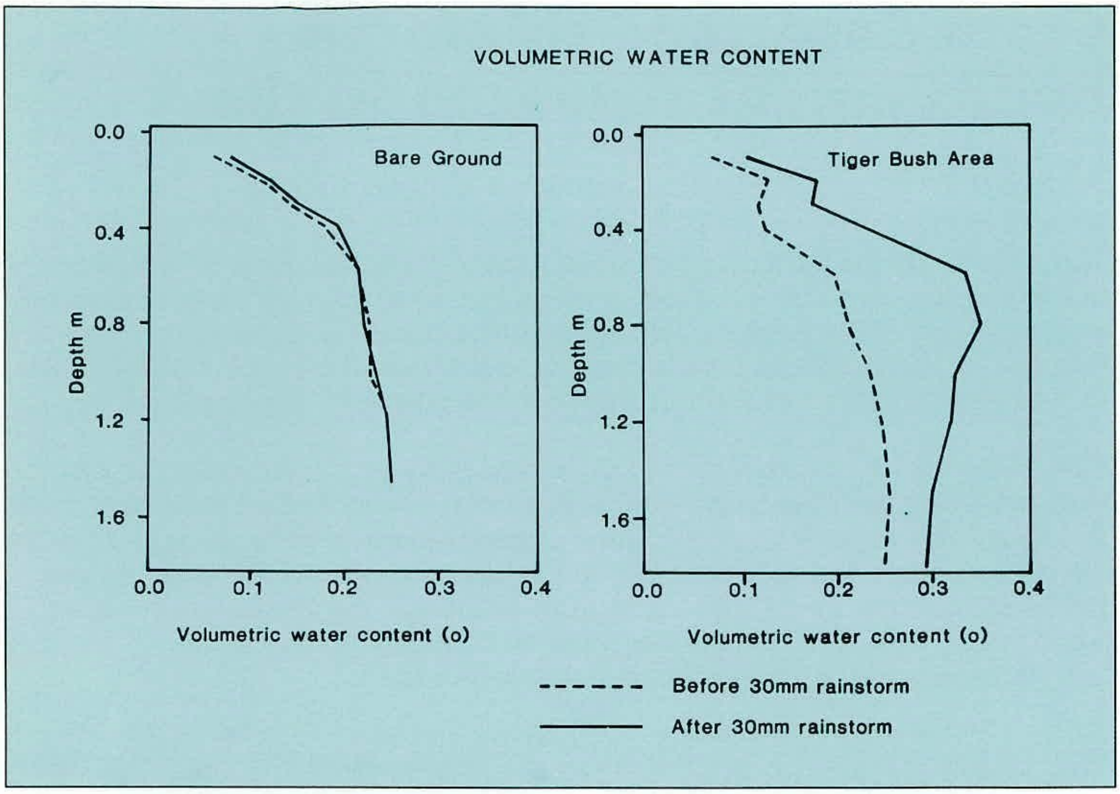


Figure 4 Diagram of the effect on soil moisture of differential recharge rates under the dense bush and soil strips which make up the Tiger bush vegetation in the Sahel. The water available below bare soil is hardly increased by a 30mm rainstorm; that beneath the bush is significantly increased.

L'effet produit par les taux de recharge différentiels, dans la brousse tigrée du Sahel, sur l'humidité du sol. L'eau disponible sous sol nu n'est pas accrue par une averse de 30 mm; celle mesurée sous végétation est accrue de manière significative.

of soil erosion, are an attractive option for village scale food production. The Institute is researching the development of this agricultural practice in Zimbabwe, in collaboration with the Lowveld Research Station and the British Geological Survey. Groundwater supplies are being tapped by 'collector wells' and used in conjunction with low cost methods of distribution and conservation of water to improve the efficiency of water use.

Elsewhere in the world the demand for fuel wood has stimulated the planting of fast growing trees. There is widespread concern, however, as to whether these in turn are detrimental to the environment, in particular, that they reduce the regional water resource. Results from the Institute's study of this problem in Karnataka State in southern India show that when water is strongly seasonal and limited in amount, the annual water use by indigenous forest and *Eucalyptus* are much the same. However, both types of forests use more water than agriculture, perhaps twice as much as the *Ragi* crop, much used in this part of India.

Water and forests

This difference in the amount of rainwater - and indeed energy - returned to the atmosphere by forests (as opposed to other types of vegetation) is the basis of concern regarding the potential impact of tropical deforestation on climate. The Institute is at the forefront of the international research effort to understand this potential problem. IH's pioneering work in Amazonia in the early 1980s provided the still unique basis for predictions using the present generation of General Circulation Models (GCMs).

These models currently lack understanding of the atmospheric interaction of clearings, and of possible feedbacks in the extent of cloud cover. The Anglo-Brazilian Amazonian Climate Observational Study (ABRACOS) is IH's major ODA-sponsored initiative to provide the

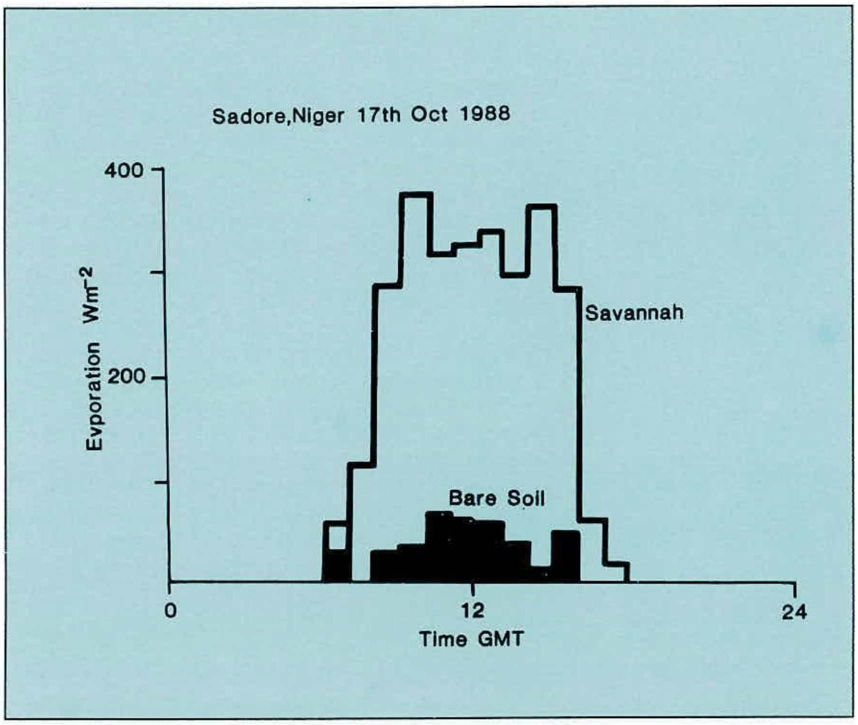
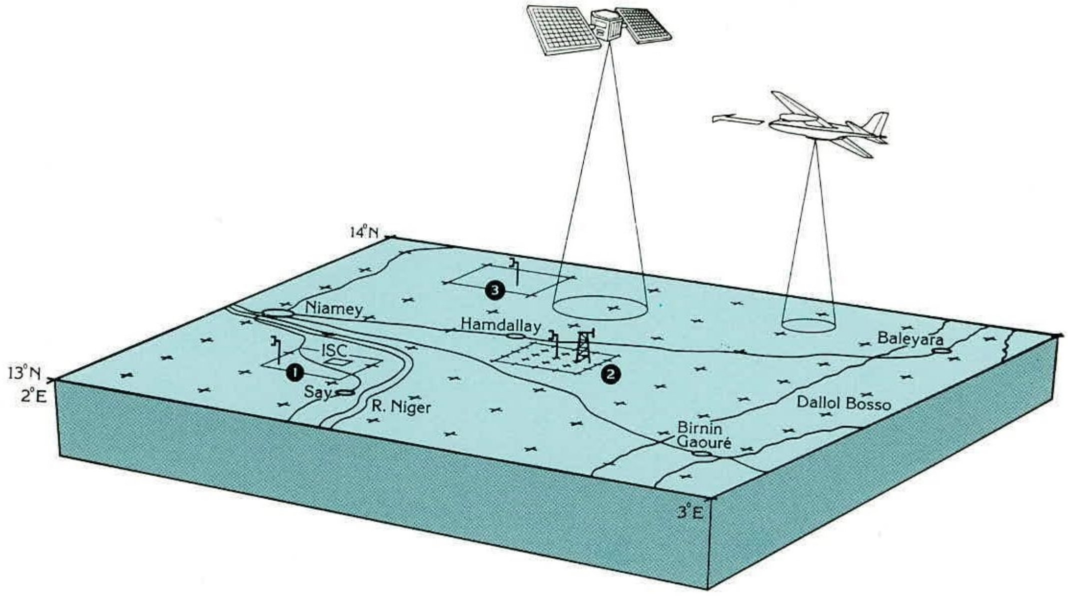


Figure 5 Evaporation rates from ungrazed savannah and bare soil, the limiting covers in dryland degradation, illustrate the large difference in evaporation from the two types of surface. Over the entire day the savannah evaporated 4mm of water, nearly ten times more than the loss from the bare soil of only 0.5mm.

Les taux d'évaporation d'une savane non pâturée et d'un sol nu, qui représentent les deux extrêmes du couvert végétal en terrains secs et dégradés, sont très différents. Au cours d'une journée, la savane a évaporé 4 mm d'eau, soit près de dix fois la perte de 0.5 mm enregistrée sous sol nu.

Figure 6 HAPEX-Sahel will provide simultaneous satellite, aircraft, surface and sub-surface measurements of energy, water and CO_2 exchange for a representative 10,000 km^2 area in the Sahel, with attention focused on three sites along the north-south precipitation gradient.

Le projet HAPEX-Sahel recueillera, à partir de satellites et d'avions, des mesures des échanges d'énergie, d'eau et de CO_2 en surface et dans le sol, pour un bassin de 10,000 km^2. L'attention sera centrée sur trois sites le long du gradient nord-sud des précipitations.



observational data required for GCMs to make accurate and credible predictions of the climatic change which may result from large-scale Amazonian deforestation. Early measurements have already revealed very significant differences in the energy and water returned to the atmosphere by forests and clearings, and distinct differences in the near-surface climates during the drier portions of the year (see Figure 7).

But the atmospheric components are not the only aspect of the hydrological cycle which is changed when tropical forests are removed. In mountainous areas, removing the trees exposes vulnerable soils to heavy and persistent rain, with soil erosion and nutrient erosion the inevitable result. These features are being studied under a new project in Nepal, carried out jointly with the Royal Geographical Society and the Central Division of Soil Science of His Majesty's Government, Nepal. Detailed monitoring of instrumented highland catchments are to provide the data for the development of models for application first in local basins and then in other basins in similar climatic/physiographic regions.

The demand for hydrological understanding associated with tropical development is a consequence of the diversity of the environments in these regions of the world, exacerbated by the rate at which they are undergoing exploitation. From deserts to rainforests, the challenge is wide indeed - as is the range of hydrological skills with which we now address it.

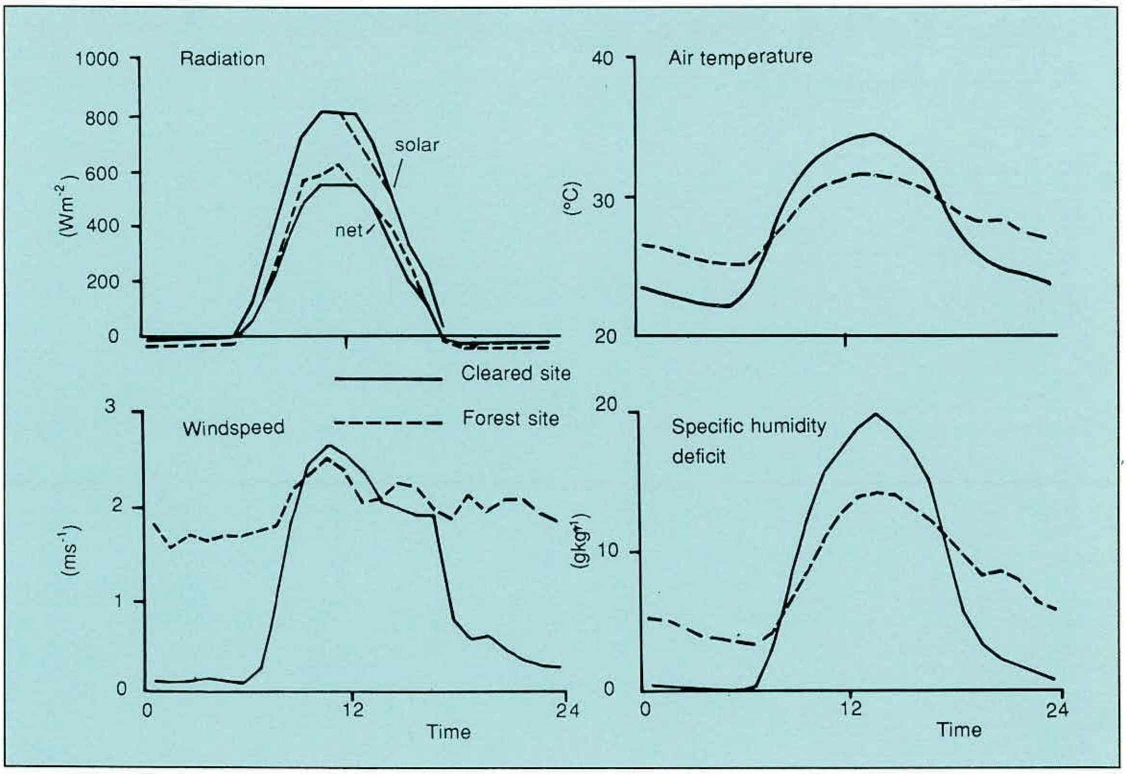


Figure 7 Comparison of the average near-surface climate within a cleared area and a nearby forest area for ten days during the dry season

Comparaison de moyennes d'indices climatiques dans une clairière et dans un bois lors d'une période de dix jours pendant la saison sèche

Soils - hydrology beneath our feet

An understanding of soil water behaviour is central to many hydrological problems. These range from determining the water balance of catchments, the direct measurement of evaporation and drainage, the genesis of streamflow hydrographs, and the fate of pollutants, including nitrates and pesticides.

The development of accurate and reliable field instruments to monitor water quantities and fluxes in the unsaturated zone has led to a greater understanding of processes, and from there to the development and use of modelling techniques in complex, real-world situations. Ongoing research into soil hydrology permeates both fundamental and applied aspects of the Institute's research.

Ponding water for the instantaneous method of measuring unsaturated hydraulic conductivity

Pesée d'eau pour la mesure instantanée de la conductivité hydraulique d'un profile insaturé

Early in the Institute's research programme, the major task for soil hydrologists was to provide the missing soil water storage term in catchment water balances. This was achieved through the development of the IH neutron probe which, for the first time ever, enabled soil water content to be measured repeatedly and non-destructively. Soil physics was thus taken out of the laboratory and into the field, so that dynamic processes could be investigated *in situ*.

Such pioneering work stimulated the adaptation and development of other new forms of instrumentation, in particular pressure transducer systems for measuring soil water potential. This, coupled with progress in computing and electronics, meant that it is possible to monitor water movement and storage in the unsaturated zone. Techniques emerged to measure directly, for example, drainage to shallow and deep groundwater, water use of natural vegetation, agricultural crops and forests (as evaporation) and soil hydraulic properties such as the unsaturated hydraulic conductivity characteristic.

A measure of the importance of this contribution to the portfolio of skills now available within the Institute is demonstrated by the involvement of soil physics in many commissioned research projects. Examples include:

- Improvement and control of drip irrigated crops (Mauritius and Sri Lanka);
- Monitoring the water use of fast-growing tree crops (India);
- Elucidating the dynamics of water movement, uptake and storage beneath natural rain forest and cleared areas (Brazil);
- Development of simple irrigation schemes relying on limited groundwater supplies (Zimbabwe);
- Dynamics of soil water movement in relation to pesticide pollution (UK);
- Semi-arid groundwater recharge (Niger).

Agricultural chemicals

Much of the Institute's pioneering work in soil hydrology has been concerned with the movement of water and solutes through the unsaturated zone overlying deep chalk and sandstone aquifers. Major contributions have been made in understanding the distinction between the two primary flow pathways in unsaturated chalk. These are slow matric flow (piston flow) through the fine pores and rapid by-pass flow through the joints and fissures (macropore flow). It was shown that the dominance of one pathway or the other depends on the unsaturated hydraulic conductivity characteristic of the chalk coupled with the amount, distribution and intensity of input resulting from rainfall and the depth of soil and weathered material over the undisturbed chalk. This has important implications concerning the manner in which nitrates resulting from fertilizers or animal slurries move to the water table.

The danger of long-term pollution of groundwater by agro-chemicals is now recognised. Some areas of the deep Chalk aquifer are already identified by the water industry as specially at risk and legislation has been passed to designate these as 'agricultural exclusion zones' in which nitrate fertilizer applications are strictly controlled. This concept will undoubtedly be extended to other areas and more sophisticated criteria applied to constrain agricultural practices and chemicals. Other techniques developed by the Institute for studying flow of water and solutes in the unsaturated zone will be particularly relevant to the research necessary to define these areas and the control criteria.

One of the most important applications of the soil physical techniques developed at the Institute has been to improve irrigation efficiency. A major interdisciplinary study of drip irrigation of sugar-

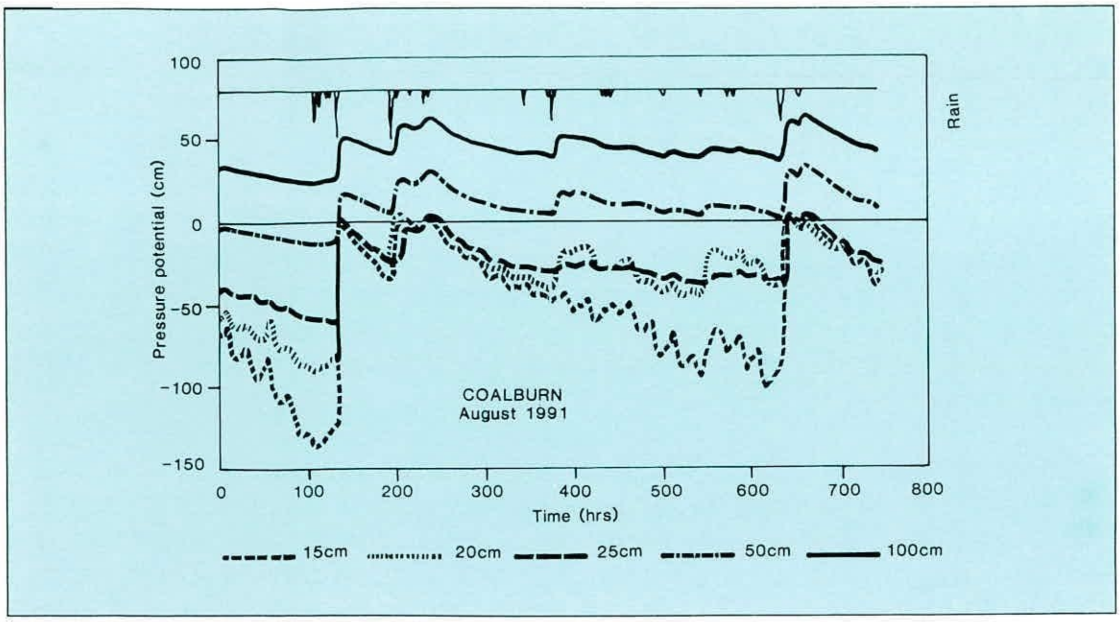


Figure 8 Soil water changes in the soil profile in response to rainfall inputs and evaporation losses

Changement de l'humidité dans le profile du sol, en réponse à la pluie et à l'évaporation.

cane in Mauritius made extensive use of this expertise and developed it further as a basis for studying the relationships between soil water distribution and irrigation regimes, dripline placement and characteristics and crop row spacings. The reasons for the differing yields of the various treatments could not have been explained without this insight into the soil water processes. Scaled down versions of these techniques are now beng applied to simpler irrigation systems for small farmers in Sri Lanka and Zimbabwe.

This work has now come full circle in that it is being applied in England to study soil water dynamics and pathways. This was part of a project to model pesticide pollution of surface waters in a drained, heavy clay-silt catchment (at Rosemaund Experimental Husbandry Farm, near Hereford). The modellers aim to predict the levels of pesticides resulting from a variety of standard agricultural applications. Arrays of tensiometers, similar to those devised for the Mauritius project, are used to study the annual cycle of the soil water potential across the field drains. Also, partition of rain between overland flow and infiltration is studied in relation to surface soil water content and rainfall intensity, thus enabling the development of models with much greater physical validity.

Differential flow processes

Soil water provides the link between storm rainfall and the changing flow in rivers and streams; the same rainstorm will result in very different streamflow patterns depending on how wet or dry the ground is. Detailed monitoring of the short term dynamics as water infiltrates down the soil profile and flows laterally to stream channels, has been carried out at sites widely distributed across Britain using electronically recording tensiometers. Figure 8 shows the pressure potentials recorded by an array of tensiometers installed at depths from 15 cm to 1 metre in a peaty gley soil; the response to rainfall inputs is apparent, together with a diurnal/daily pattern due to evaporative demand.

Significant differences have been found between sites and between storms at different times of the year, and these have been shown to have an important control on the generation of streamflow response. In addition, naturally occurring environmental tracers are used to study the source of streamflow - whether rainfall or pre-event soil water - information which is essential for the development of future physically-based models of solute movement. Results indicate that the ratio of 'new' to 'old' water may vary widely in response to the volume of water in store in the catchment at the start of the storm.

Radio-nuclide movement

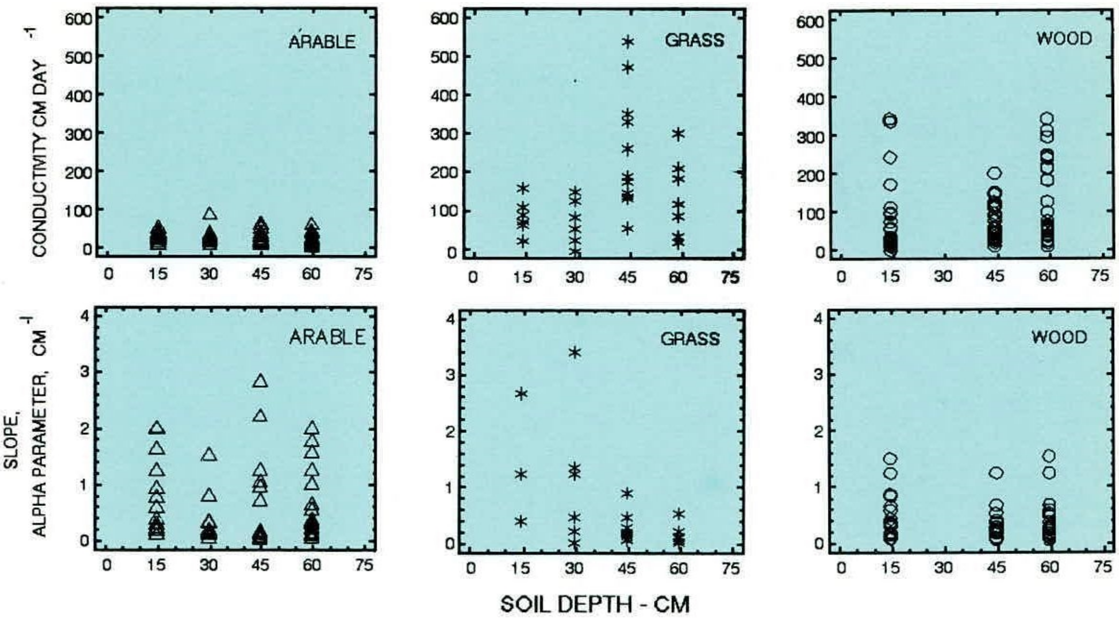
The successful modelling of soil water movement is a fundamental part of current investigations into the safety of deep radioactive waste disposal repositories. Transportation by water is the most likely pathway by which radionuclides released from such a repository may eventually reach man, and thus an adequate understanding of the process of water movement in soils and rocks is essential to assess repository safety.

A small catchment near Slapton in south Devon has been the subject of an intensive soil water monitoring exercise to collect data for use in the computer-based mathematical model SHE (Système Hydrologique Européen) which the Institute developed in collaboration with SOGREAH, France, and the Danish Hydraulics Institute.

The Slapton catchment is one of the few in the UK which has long data records for such model validation. It includes three land use domains: arable (including temporary grass), permanent grass, and woodland. For the unsaturated zone component of the model, both saturated hydraulic conductivity Ks and unsaturated hydraulic conductivity as a function of matric

Figure 9 Saturated hydraulic conductivity (Ks) and slope of unsaturated hydraulic conductivity function (ψ) of the soils in the three land use domains of the Slapton Wood catchment

Conductivité hydraulique à saturation (Ks) et pente de la fonction de la conductivité (ψ) hydraulique en conditions non saturée, pour trois types d'utilisation du sol dans le bassin de Slapton Wood



potential K(ψ) are required. These parameters were measured at four different depths, with both Ks and the slope of the unsaturated hydraulic conductivity function found to be log-normally distributed. The Ks values were highest in the grass and lowest in arable land. High values of Ks were attributed to preferential flow along slate faces and root-induced channels in the grass and woodland respectively, as indicated by dye tests.It was concluded that since Ks and K(ψ) differ significantly between domains, different hydrological behaviour would be expected and it is recommended,therefore, that independent parameter sets be used.

This work is being carried out in collaboration with Newcastle University and is funded by UK Nirex Ltd. The results will be applied to the area around Sellafield in Cumbria, which is being considered as a potential radioactive waste disposal site.

Plant-soil water relations

The flora composition of natural habitats in shallow groundwater areas may be very sensitive to changes in the groundwater regime. Changes in soil water content due to alterations of groundwater levels may cause excessive plant water stress resulting in long-term detrimental effects. The Institute has been investigating the hydrology of the shallow groundwater environment found beneath the historic water meadows outside Oxford whose flora have remained largely unchanged for centuries but which may be under threat from groundwater changes brought about by nearby gravel extraction.

Measurement of soil water conditions and plant response in terms of transpiration rate has permitted quantification of the normal water regime of this particular habitat. Transpiration rates were found to be less than the potential evaporation rate for much of the year. It was expected that in spring transpiration would be similar to potential evaporation while the water table level remained high. However, the transpiration rate did not reach the potential rate until the end of May. Thereafter the combined effect of the falling water table and the hay cut caused the transpiration rate to decrease below the potential rate once more.

Future developments

The search for quicker and easier ways to measure water in the soil is a constant feature of soil physics research. An important development in recent years has been the successful deployment of capacitance probes, particularly for measuring water content in soil near the ground surface. The Institute's surface capacitance probe is adaptable to measure the top 5 cm and the top 10 cm water content and has now been tried at a variety of sites. The good agreement found between different areas is very encouraging for the future of this instrument.

The IH capacitance probe has enabled the spatial distribution of surface soil moisture to be measured within grassland test sites for evaluating the sensitivity of airborne microwave radar to soil moisture. The work was part of an EC initiative in microwave remote sensing to prepare for the use of satellite radar data from ERS-1 and from similar satellites which will operate to the end of the century.

Satellite remote sensing should, in the future, provide a measure of soil moisture variability which cannot be obtained from ground data measurements alone. The ability of microwaves to penetrate cloud is crucial to the application as frequent observations are required to monitor spatial changes in soil moisture. In the UK, three test sites will provide control measurements for the evaluation of ERS-1 radar over a range of soils exhibiting relatively high soil moisture levels. For evaluation of dry soils, additional soil moisture data will be collected within the HAPEX-Sahel sites in Niger (see also page 9).

Climate change impacts

Climate change became one of the biggest scientific issues during the 1980s and is likely to maintain its high profile during the present decade. One of the greatest impacts of climate change will be on the hydrological system, and hence on water resources, ecological systems and, possibly, economic development.

A greenhouse-gas induced climate change would affect both the inputs to the hydrological system - precipitation, evapotranspiration and atmospheric deposition rates, for example - and the operation of processes within the system. A change in soil structure due to alterations in rainfall regimes and vegetation cover would affect flow paths, which would influence both the quantity and quality of water in a stream. Higher temperatures would alter biogeochemical process rates. Changes in catchment vegetation cover and dynamics would affect seasonal evapotranspiration. At the same time, hydrological processes feed back into the climate system. Evapotranspiration processes control fluxes of water and energy, and the timing of inflows into wetlands can control the timing and rate of regional evaporation.

Several studies into the hydrological impacts of climate change are currently under way at IH. The Department of the Environment (DoE) is supporting a 'core modelling' programme which is developing physically-based methods of estimating impacts on ecological and water chemistry processes. DoE's Water Directorate has commissioned an assessment of the impacts of climate change on water resources in the UK, considering both water quantity and water quality, building upon an earlier study completed in 1990.

At a somewhat larger spatial scale, the Overseas Development Administration has recently begun funding a project to estimate potential changes to water resources in East Africa.

It is currently too early to make definitive predictions of future changes in regional climate, so all IH impact assessment studies use a range of realistic climate change scenarios. These scenarios are internally-consistent estimates of possible change, and are based on the qualitative interpretation of climate model output. They have so far been used to determine the sensitivity of hydrological systems to future climate change, and not – yet – as forecasts of the future.

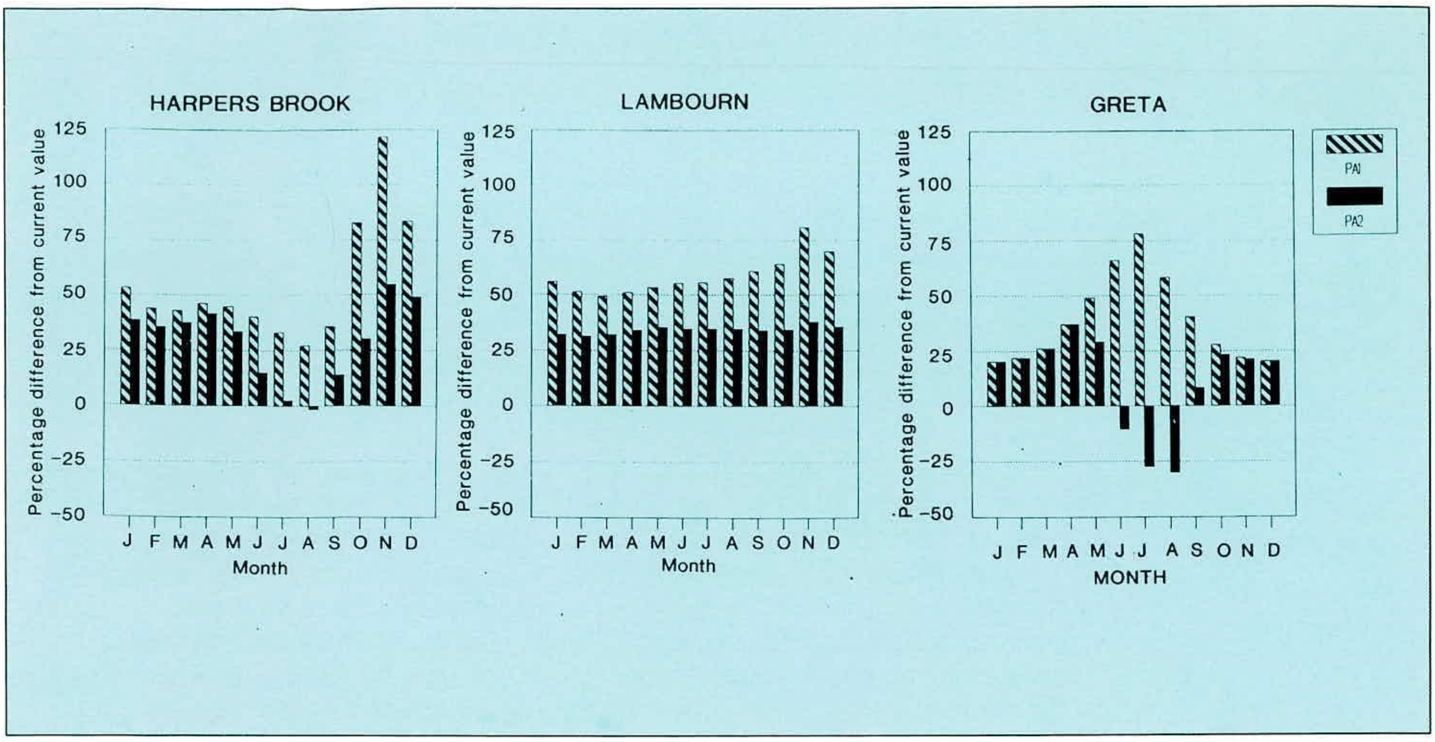
Climate change may have profound implications for future water resources.

Le changement du climat pourrait avoir des répercussions profondés sur les ressources en eau du future.

River runoff recorded at the outlet of a catchment reflects the integration of a time series of climate inputs with catchment physiological, geological and climatic conditions. The effect of a given climate change scenario therefore varies between catchments. Figure 10 shows two climate change scenarios applied to three different English catchments. Scenario 1 assumes that rainfall increases by 20% throughout the year, whilst scenario 2 assumes that an increase of 20% in winter is counteracted by a reduction of up to 15% in summer: annual rainfall increases by between 10 and 12%, depending on the current distribution of rainfall through the year. Potential evapotranspiration is assumed unchanged (this is unrealistic, of course, but the Figure is designed to show sensitivities to change, not forecast future flow regimes). The river flows in each catchment are estimated by a monthly water balance model, and the scenarios are applied by perturbing the historical time series of catchment monthly rainfall and potential evapotranspiration.

The Greta is an upland catchment, with a fine balance in summer between rainfall and potential evapotranspiration. A reduction in rainfall (Scenario 2) tips the catchment into a summer water deficit, and summer runoff reduces by a large percentage; an increase in rainfall (Scenario 1) produces a surplus of water, and accordingly runoff increases by a large percentage.

The Harpers Brook, in contrast, is a responsive lowland catchment where rainfall in summer is considerably less than potential evapotranspiration. Little of the summer rainfall produces streamflow, so a change has limited effect on summer flows: The greatest effects are, instead, noticed in autumn. Lower summer rainfall means that larger soil moisture deficits build up and so it takes longer for deficits to be eliminated in autumn; higher summer rainfall means that the



catchment returns more rapidly to a saturated condition. Flows in the third catchment, the Lambourn, are controlled by drainage from a chalk aquifer recharged each winter. The extra winter recharge under Scenario 2 means that flows during summer are increased even if summers become drier.

The actual magnitude of changes in flow regimes will depend on the magnitude of change in the climate inputs: an increase in winter rainfall, for example, may be insufficient to compensate for a shorter recharge season due to increased evapotranspiration, and flows may therefore be reduced all year round.

Current studies are using daily water balance models in an attempt to refine further assessments of the effects of catchment type on response to climate change. The studies will also be using climate change scenarios consistent with those adopted in other UK impact assessments, and will concentrate more on forecasting possible future flow regimes.

Figure 10 Change in mean monthly flows under scenarios 1 and 2 for three example catchments. Potential evapotranspiration is unchanged.

Changement du débit mensuel moyen sous les scénarios 1 et 2 pour trois bassins. L'évapotranspiration potentielle est inchangée.

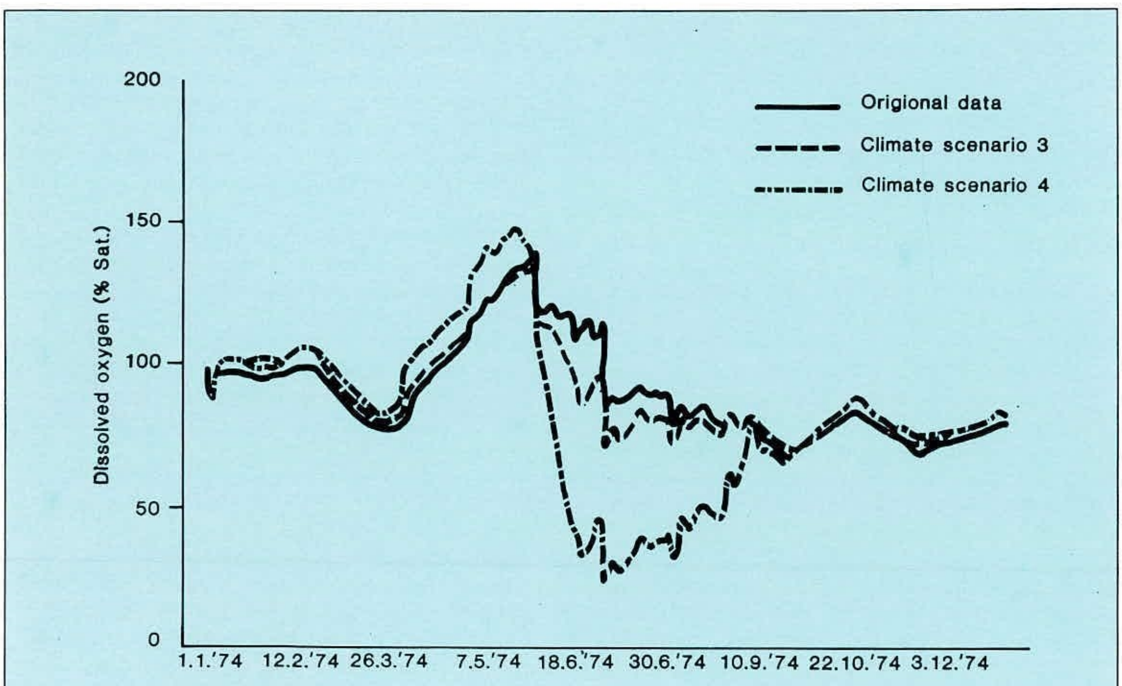


Figure 11 Original dissolved oxygen (% saturation) at Datchet on the River Thames in 1974, compared with the dissolved oxygen under extreme climate change scenarios

L'oxygène dissout (en % de saturation) à Datchet sur la Tamise en 1974, comparé à l'oxygène dissout dans le cadre de scénarios de changements climatiques extrêmes.

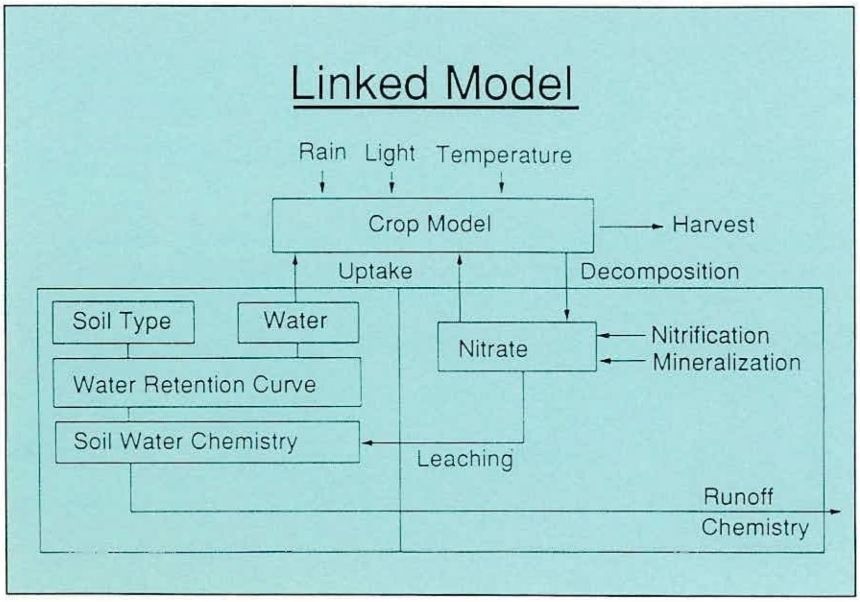
Changing river flow regimes, together with changing atmospheric inputs, increasing temperatures and changes in flow pathways, will also lead to changes in stream water quality. Flow pathways might change as a result of increased temperature leading to higher evapotranspiration rates and hence drier soils. Changes in flowpath and residence time will influence soil-soil solution equilibrium reactions and so alter the chemistry of streamwater: minerals could be released into soil water through sulphur and nitrate mineralisation as the soil dries and microbial action increases.

Studies using the Institute's operational water quality model QUASAR have looked at the effects of rising temperatures on ammonia and nitrate levels in rivers. Both nitrification and denitrification rates increase as temperatures rise but because ammonia levels are initially much lower than nitrate, the denitrification rate outstrips the nitrification rate and nitrate levels fall. On the other hand, QUASAR simulations of the River Thames showed that dissolved oxygen content reduced as temperature increased. Figure 11 shows the effect of two scenarios of increasing temperature on simulated dissolved oxygen concentration in the River Thames (Scenario A: an increase of 2.3 degrees, Scenario B: an increase of 3.5 degrees). The effects of temperature changes, however, are superimposed on changes in flow volumes, and these in turn will be superimposed upon changing management strategies, causing large uncertainties in system response.

Some of the biogeochemical processes affecting the response of stream water chemistry to climate change are being investigated in more detail using physically-based models linking water chemistry, soil chemistry and nutrient uptake by vegetation. The models are dynamic, and will - ultimately - incorporate all the relevant feedback mechanisms controlling stream biogeochemical fluxes. Figure 12 summarises the links between the component models.

Figure 12 The biogeochemical models currently being developed are linked in this structure.

Les modèles biogéochimiques en cours de développement sont liés dans la structure illustrée par la Figure.



Changes in both water quantity and water quality will feed through to water resources, geomorphological and ecological systems, but the effects of change will depend on the sensitivity and buffering capacity of the "receiving" system. The greater the amount of storage within a system, the better that system is able to cope with change; the closer the system is to its operating limits, the more sensitive it will be to change. A water supply utility with a large reservoir and low demands, for example, will be less affected than a utility with a number of small reservoirs and high demands. Similar principles apply to geomorphological and ecological systems, and it is difficult both to estimate the 'impact' of climate change - in monetary units or square metres of lost habitat - from hydrological changes alone, and to make grand generalisations.

Modelling obviously has a very important role to play in future climate change impact studies. Water resources impacts need to be estimated by combining a model of the water resources system (and its ability to respond to change) with models of the hydrological system, and very few climate change impact studies have yet made this linkage. In the hydrological modelling field, there are two main areas of particular interest.

One is the application of physically-based models to estimate changes in processes that will be associated with climate change: the biogeochemical and linked hydrological-ecological modelling currently being undertaken for the Department of the Environment is an example.

The other is the development of large-scale hydrological models that operate over extensive regions and which are capable of linking directly with climate models. Such a model would use gridded inputs from a climate model to simulate hydrological regimes at all grid cells within a large basin, and would integrate flows from individual cells to simulate total basin runoff. The model would not only be valuable for estimating the impacts of climate change - or indeed any environmental change - in a large basin, but could also feed back hydrological information on inflows into wetlands or the ocean into a climate model. The GEWEX Continental Scale International Project (GCIP) has been created to develop such a model, using the Mississippi catchment as a test-bed, and IH is playing a leading role in the formulation of this major international project.