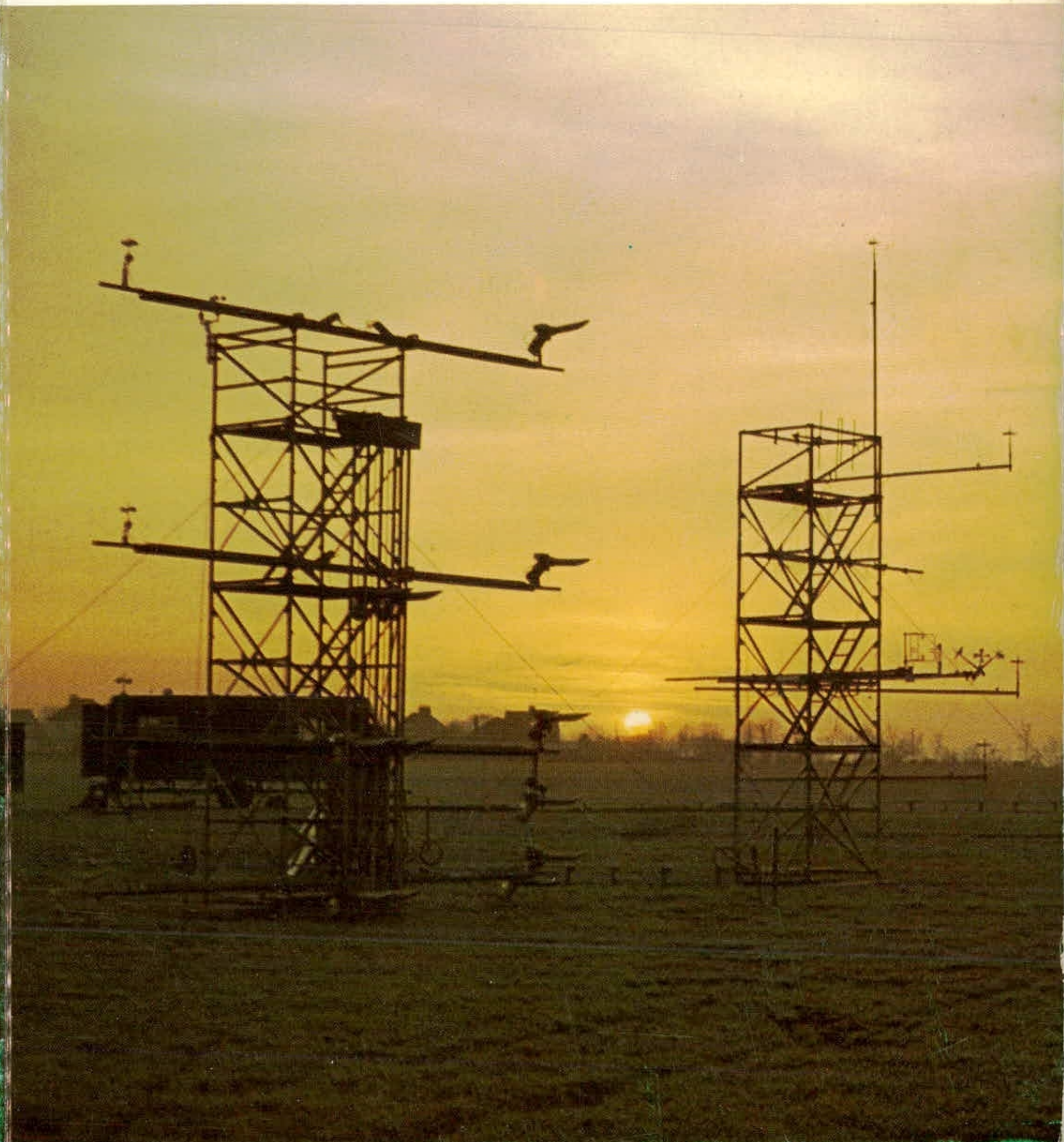
Institute of Hydrology

Research Report 1976-8



The Institute of Hydrology is a component establishment of the Natural Environment Research Council which itself is grant-aided by the Department of Education and Science. The Institute's research programme is in three main parts: firstly, the exploration of hydrological systems within complete catchment areas; secondly, fundamental studies of the behaviour of water in its main phases in the hydrological cycle; and thirdly, applied studies concerned with flow prediction, water resources surveys or operational studies.

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Front cover: *Sunrise over Stadhampton field site* – see page 42

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Natural Environment Research Council

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Director's Review

"Do forests use more water than does grassland?" This question, twenty years ago, was asked on many occasions in the United Kingdom and in many overseas countries with real or potential water resource problems. There was no shortage of answers from competent well-qualified professionals in a variety of disciplines. The forester, who planned to extend plantations, considered trees the optimum land use for maximising rainfall and retaining snowfall, for inducing infiltration of water into the soil and prolonging dry season streamflow and for minimising surface runoff and hence soil erosion. The agriculturalist argued that arable cropping would maximise water availability because at planting and at harvest, transpiration would be minimal; in upland catchment areas, sheep or cattle on well-managed hill pastures would not adversely affect the water resources of the area. Faced with such diverse expert opinions, the engineering hydrologist was worried, particularly in the light of the Forestry Commission recommendation to afforest catchment areas of reservoirs; calculations of storage and yield of these reservoirs had been made on the basis of continuity of behaviour of the catchment area above the dam and not on the assumption that the streamflow might be affected in quantity or in seasonal distribution as the trees grew larger. The physicist, if invited to comment, stressed the laws of continuity of matter and energy: evaporation from a catchment was largely determined by the meteorological environment and was dominated by the net radiation received in the catchment. Since convection and heat storage terms tended to be small as compared to the input of solar energy, all greencrops would, as a first approximation, "use" the same amount of water; differences between crops would be largely due to differences in albedo and hence in the net radiation. The logic of this advice was irrefutable. Yet still doubts remained and, the world over, scientists both individually and in groups inclined towards experimentation to decide the issue. Statisticians pointed out the problems of extrapolation from unique or even replicated samples and suggested that all the relevant variables should be included at different levels in the experimental design; the importance of randomisation was paramount.

In East Africa in 1956, a group of scientists, agriculturalists, foresters, engineers and administrators agreed on proposals for detailed catchment area research in four areas considered representative of the range of environments present. This was followed in the UK by recommendations in 1962 by the Department of Scientific and Industrial Research Committee on Hydrological Research for the establishment of a research unit to investigate the hydrological consequences of changes in land use in upland catchment areas. At UNESCO in Paris in 1964 a massive international plan, largely based on catchment area research was initiated; it was called the "International Hydrological Decade".

Both the East African and the UK catchment research projects contributed national data to the IHD. Both have been operated, partly so in East Africa and wholly so in the UK, by IH staff. And, during the present biennium, the results of both series of experiments have become available. These results, in conjunction with detailed physical process studies (undertaken as part of the fundamental research programme of the Institute so that the scientific results from particular systems studies might be applied to environments beyond the range of statistically valid extrapolation) have substantially increased human understanding of the hydrological cycle. Over this period there have been major advances in environmental instrumentation and in capability for computation which were hardly contemplated at the outset. These advances and these results together enable the hydrometeorologist, in locations for which perhaps only the simplest hydrological measurements of rainfall and streamflow may be available, to establish his battery powered automatic weather station, to take measurements or make estimates of the physical "crop" factors, and to deduce from these observations and from the past results the quantitative consequences of a change in land use.

What then, was the true answer to the original question on the water use of trees versus grass? And where did all the various experts go wrong in their prognostications? This is not the place for a full and detailed scientific answer to the original question: this is already available in print in various of the publications listed in the references at the back of this report. The short answers, respectively are "It all depends" and "On the whole, they were all right except for the forester who thought that trees somehow generated rainfall, and for the physicist who had over-lightly dismissed the effect of storage and of advection of heat". The Plynlimon comparison of forests versus mountain sheep pasture shows that forests in a wet up land environment can evaporate $1\frac{1}{2} - 2$ times as much as grassland. The Kenya comparison of water use of pines as compared to bamboo and of the water use of tea as compared to montane rain forest indicates that the evaporation from exotic forestry or plantation crops differs little from that from indigenous forest or bamboo.

The key to an understanding of these results, which at first sight seem inconsistent, is an appreciation of the role of rainfall interception in evaporation from vegetation. Short crops completely covering the ground (as defined by Penman in his original papers on evaporation), exert little control on transpiration because their stomatal resistance is low except when moisture is limiting. For all practical purposes therefore, the transpiration which occurs from such short crops differs little from the evaporation from water intercepted by the leaves of the same crop after rain; both can be approximated closely by the Penman estimate. Tall crops such as forest, however, exert considerable control on transpiration; the surface resistance of dry forest is high so that transpiration is substantially less than the Penman estimate and may be only a fraction (40%) of the net radiation. When the forest is wet, on the other hand, the surface resistance tends to zero and the evaporation of intercepted water proceeds at a much higher rate than that predicted by the Penman estimate; it may even substantially exceed the net radiation input, the balance of energy being supplied by advection and by cooling of the forest itself.

This understanding of the role of intercepted water and of the importance of the physical and biological controls of transpiration, can be applied to results of catchment experimentation the world over. No longer must expensive and time-consuming catchment area research be conducted in each climatic zone with each vegetative cover; rather the results of competently executed experimentation can be extrapolated to environments beyond the range of the original investigations.

J S G McCulloch
Director

Hydrological Systems

Hydrological modelling of catchment behaviour

Spatially-uniform models

For some purposes, it is convenient to assume (a) that the hydrological processes by which rain falling on a catchment is converted to streamflow are spatially uniform; (b) that the rainfall itself (regarded as 'input' to the catchment, or 'system', yielding streamflow as its 'output') is also uniform in distribution. A model which uses these two assumptions to give estimates of streamflow when rainfall is known is frequently termed a 'lumped' model to distinguish it from one that takes account of catchment topography and the varying proportions of infiltration and surface runoff over it. Models of the latter type are 'distributed'.

The Institute's work on lumped models began in the late 1960s, and the model that has been devised represents catchment behaviour by three reservoirs or 'stores', with fluxes of water between them governed by plausible mathematical relations incorporating the known characteristics of such transfers. For example, when rain falls on a dry catchment with a large soil moisture deficit (when, in the terminology, the contents of the soil-moisture store are small) the proportion of rainfall that infiltrates into the soil is larger than when the catchment is saturated. The three stores in the current version of the model are (a) an interception store, describing how vegetation intercepts a part of the precipitation which is later lost by evaporation; (b) a soil moisture store, with contents controlling the rates at which rapid runoff and percolation to groundwater occur; (c) a groundwater store, yielding the baseflow component of streamflow. Full descriptions of the model have been given in earlier Institute reports.

Unknown constants appearing in the functional relations describing water transfers from one hypothetical store to another are estimated by minimising the value of some function: typically, this function is the sum of squared differences between observed streamflows over, say, daily time intervals, and the corresponding streamflows predicted by the model. This sum of squares, regarded as a function of the unknown constants ('parameters') is termed the 'objective function', and the procedure for calculating least squares estimates of the parameters is 'optimization'. Clearly, models of this type may be used only where there exists a relatively long and reliable record of streamflow.

In recent years, a detailed examination of the model structure and further development of the computer programs has resulted in more efficient calculation and improved methods for presenting the computed results. Until such time as sufficiently long runs of data are available from Plynlimon, data from the Ray, Cam, Coalburn and the East African catchments have been used in testing alternative functional representations of the interstore transfers. Most of this work has used daily streamflow totals, on the basis that, in the application of the model for forecasting purposes to non-experimental catchments, this is the shortest time interval of streamflow data likely to be available.

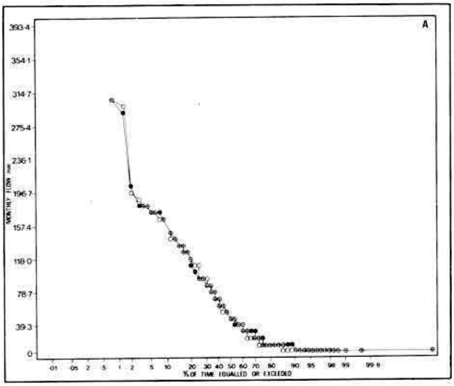
Using essentially similar versions of the model and progressively optimising up to 16 parameters, the model was first fitted using a part of the available record of daily streamflow (usually 2–4 years), and then used to estimate daily streamflow, given the rainfall, for the remainder of the period of record ('prediction period', in the table opposite). With efficiency defined as in earlier records, model performance was as shown.

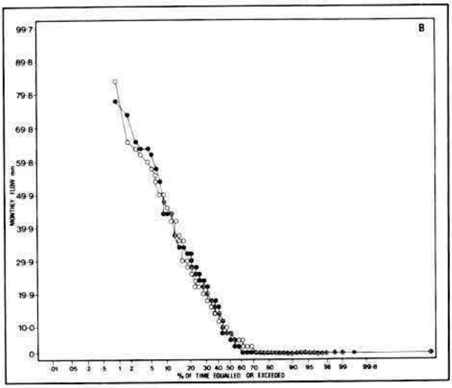
Flow duration curves for observed and predicted monthly flow for the catchments are illustrated in Figure 1.

So far, it seems that lumped models of the above type have two principal applications. First, they are of value for estimating daily streamflow where rainfall has been recorded for a period longer than streamflow has been measured; second, they facilitate the detection of the start of systematic errors in rainfall or streamflow

Table 1. *Model performance for Kericho, Ray and Cam catchments.*

Catchment	Kericho at Sambret	Ray at Grendon Underwood	Cam at Dernford Mill
Land Use	Bamboo forest	Arable farming and pasture	Mainly arable
Area (ha)	186	1860	19700
Mean Annual Rainfall (mm)	2036	637	587
Mean Annual Streamflow (mm)	807	174	163
Prediction Period (yr)	14	12	10
Error in Total Flow Volume	−0·7%	+1·5%	+1·7%
Efficiency	0·95	0·70	0·81





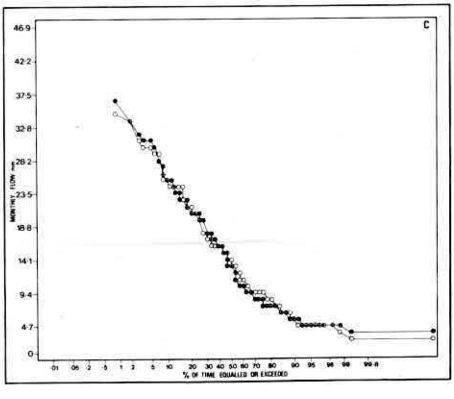


Figure 1. *Observed and predicted values for monthly totals plotted as a percentage of the time equalled or exceeded, for (a) Kericho, (b) Ray and (c) Cam catchments*

measurement, or of sudden inadvertent changes in catchment response. For example, detailed investigations of the progressive departure of cumulative observed and predicted flows from the Cam catchment, illustrated in Figure 2(left), was traced to a systematic error in rainfall data processing; the effect of correcting this error is shown on the right. The parameters of lumped models have not so far proved useful for quantifying the hydrological consequences of land-use changes, partly because the least-squares estimates of model parameters are strongly correlated, and partly because of consistent biases in the data used to calculate them.

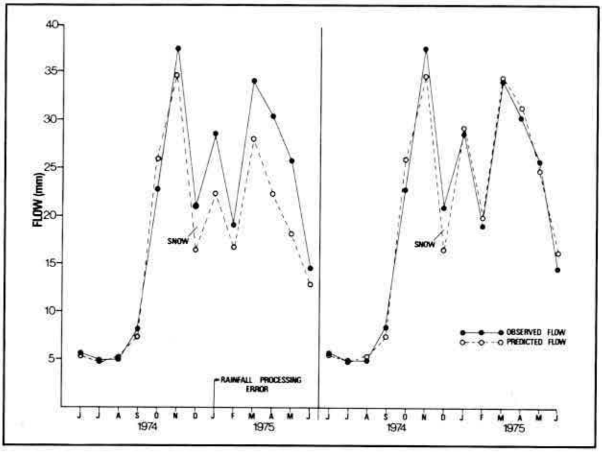


Figure 2. *Predicted and observed hydrograph for River Cam at Dernford Mill from the end of a ten-year data set. The predicted flow is obtained from a lumped conceptual model using rainfall and Penman potential evaporation as inputs on a daily interval. The rainfall processing error is clearly shown by the divergence of the hydrograph in January 1975*

The use of field observations in a model of a subcatchment of the River Wye

Lumped catchment models such as those described above require streamflow, rainfall and meteorological data for the estimation of model parameters, but rarely make use of other field observations of areal extent of natural water storages (such as peat-hags), or of measurements of the relation between discharge from such hags and the depth of water stored in them. Work has been in progress to find some way of using such information to assist in calibrating a modified lumped model of a subcatchment (area 0·026 km^2) of the Wye at Plynlimon. The subcatchment consists of (a) a hill-top area of peat hags (4768 m^2) and bare channels between them (4288 m^2) called the 'upper tank' in the model; (b) grassy slopes intersected by a network of natural pipes (8640 m^2) called the 'middle tank'; (c) a marshy area in the valley bottom called the 'lower tank'. Figure 3 shows the model structure, and how rain falling on peat-hag, bare channel, grass slope or valley bottom is routed to the catchment outfall. The relation between discharge RO_i from each secondary store in the model is related to depth of water ST_i in it by the non-linear relation $RO_i = RK_i (ST_i)^{RK_i}$ (i = 1, . . . 5). The model parameters are therefore as follows:

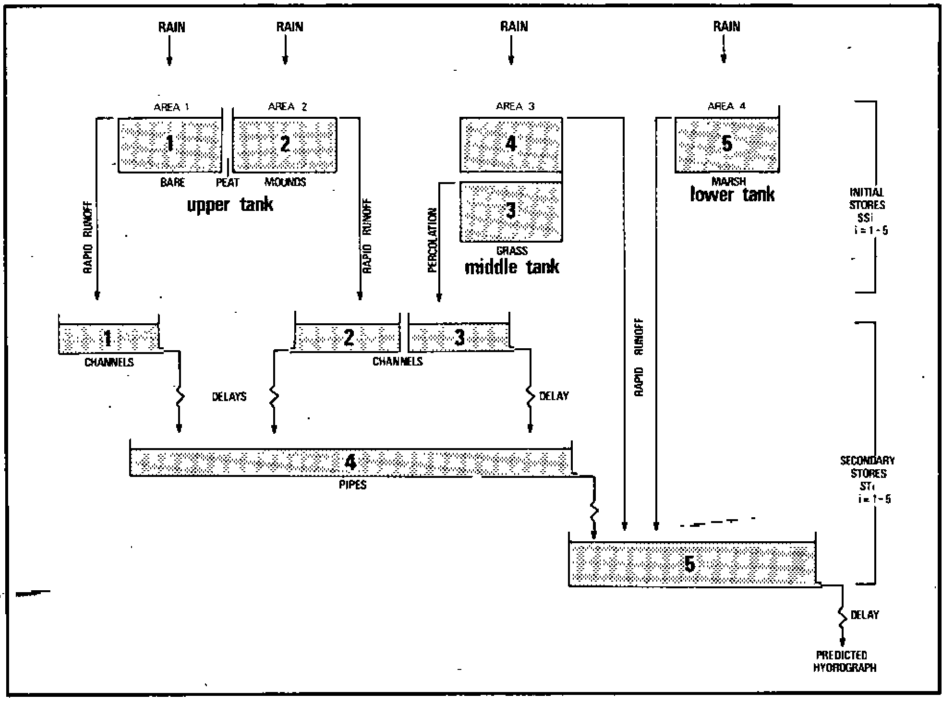
a The initial depths of water present in each of the stores SS_i (i = 1 . . . 5);

b The initial depth of water in each of the secondary stores ST_i (i = 1 . . . 5);

c The coefficients RK_i in the non-linear storage relations given above;

d The exponents RK_i in those relations;

Figure 3. *The IH 'tank' model*



e RC, the percentage of rainfall on grass slopes (Area 3 of Figure 3) which percolates into secondary store 3;

f The delays DEL_i in runoff from the secondary stores ($i = 1, \ldots 5$).

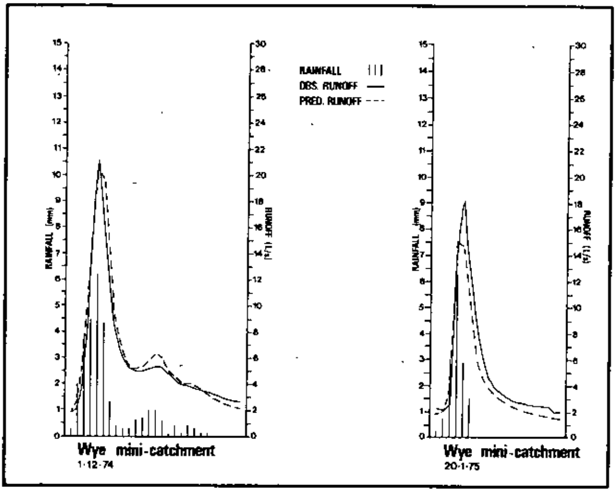


Figure 4. *Measured and predicted hydrographs for Plynlimon catchments for two storms with similar initial conditions*

Figure 4 shows measured and predicted hydrographs for two storms with similar initial conditions in the catchment. The parameters SS_4, ST_i ($i = 1, \ldots 4$), and RK_i ($i = 1, \ldots 4$) were determined from field measurement, and the remaining parameters were determined by averaging values obtained by minimising a least squares objective function calculated for each storm separately; further work is required before the model can be satisfactorily applied to other storms.

Deterministic, distributed rainfall-runoff models

The Institute is collaborating with two European Institutions (the Danish Hydraulic Institute and SOGREAH of Grenoble) to develop a comprehensive distributed model, firmly based on physical principles and making full use of field measurements of soil moisture characteristics and hydraulic conductivities. This model is called SHE (Système Hydrologique Européen) and its purpose is to predict the hydrological consequences of land-use changes, whether or not streamflow records exist for a basin. It is intended that computer programs for the model will be commercially available in the early 1980s, when work will commence on a further development to include the description of water quality changes.

Work on SHE complements work on developing distributed models of the Plynlimon catchments; emphasis on the latter concerns the catchment's response to heavy rainfall, whilst the former also includes the study of evaporation and transpiration losses between storms. Progress in both projects is now described under separate headings.

A deterministic, distributed model of the Plynlimon catchments

Work continues on a model of the Plynlimon catchments in which each is divided into areas represented by 'slope elements' or 'channel elements'. A slope element represents part of a hillside and consists of a layer of soil with constant thickness resting on an inclined impermeable stratum. The area and inclination of a slope element, which is rectangular, is arranged to be equal to the area and average inclination of the hillside it represents. Channel elements represent sections of the major streams and are straight with rectangular cross-sections. The flow of water over the surface of the slope element or in a channel element is described by the Saint-Venant equations, the first of which expresses continuity and the second the equality of force to rate of change of momentum:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(uh) = q$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\cos\theta\frac{\partial h}{\partial x} = g\left(\sin\theta - \frac{u^2}{C^2 h}\right) - \frac{qu}{h}$$

where h is depth of water (L^{-1}), u is velocity (LT^{-1}), x is distance downslope (L), g is acceleration due to gravity (LT^{-2}), C is the Chézy roughness coefficient ($L^{1/2}T^{-1}$), q

is lateral inflow per unit time per unit length of channel or slope (LT^{-1}), and θ is slope angle. Flow within the soil is described by the Richards' equation for flow in a porous medium:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z} (K(\psi) \frac{\partial\psi}{\partial z}) + \frac{\delta K}{\partial z}$$

where θ is volumetric water content (dimensionless), ψ is matric potential (L), $K(\psi)$ is hydraulic conductivity (LT^{-1}), and z is depth (L).

The numerical procedures for the solution of these equations have been explored, as has the point when simplified boundary conditions can be assumed, thereby facilitating the numerical solution whilst retaining physical validity. A new implicit method for the solution of the Saint-Venant equations has been devised and has proved efficient and stable in use. An alternating-direction implicit method of solution of the Richards' equation has been used successfully to model flow in unsaturated zones, and an iterative method is being developed to model flow in the saturated zone.

The surface runoff component of the model has been used to simulate the response of the Plynlimon catchments to heavy storms when the soil is already saturated. Flow data are available for the Wye catchment and three subcatchments within it, those of the Nant Iago, Cyff and Gwy. The geometries of these catchments are varied; the Nant Iago is represented in the model by three slope elements and a channel element, the Cyff by five slope elements and two channel elements, and the Gwy by eight slope elements and three channel elements. The Wye consists of the sum of all these elements plus four more slope elements and one further channel element. However, Figure 5 shows that a reasonable prediction of all the hydrographs can be made using the same values of Chezy roughness, $C = 19\ m^{1/2}s^{-1}$ for the channel flow and $C = 0{\cdot}47\ m^{1/2}s^{-1}$ for overland flow on the grassy slopes for each catchment. The solid line shows the measured hydrograph and the broken line the predicted hydrograph. The value of C for the grassy slopes is an order of magnitude less than the values measured on small experimental

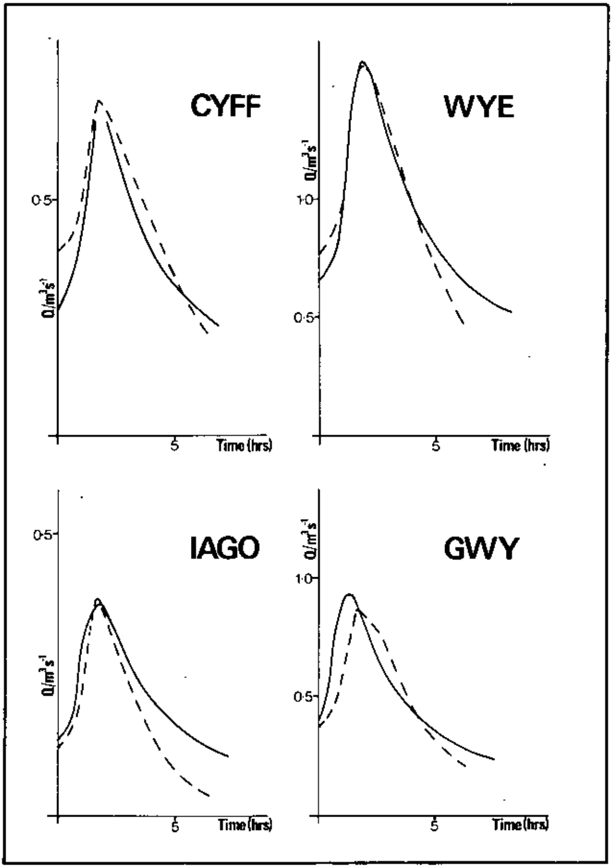


Figure 5. *Measured and predicted hydrographs for the Plynlimon catchments*

grass plots, but this is not surprising since on the large scale the roughness coefficient must describe not only the small scale roughness of the vegetation, but also fluctuations in terrain that can give rise to the formation of small rivulets within hollows.

European Hydrological System (SHE)

Work on the development of SHE began in October 1976 and concentrated during the first year on the formulation and testing of individual model components. The overland and channel flow components are the responsibility of SOGREAH; IH is responsible for the interception, evapotranspiration and snowmelt components (see below), and the Danish Hydraulic Institute for flow in the unsaturated zones and for the design of the computer program assembling the model components. All components have now been developed, and work is in progress to link them together.

The evaporation component The model uses the Penman-Monteith equation to describe evapotranspiration and the Rutter model for the evaporation of intercepted water. However, since the parameter values required for these equations may not be available for all vegetation types, flexibility is retained in the model structure so that other approaches may be used according to the data available. Sensitivity analyses have shown which parameters in the description of interception and evaporation require the most precise estimation, and a survey is in progress of published parameter values for different crops in different regions to serve as a reference for applications of the SHE model.

The snowmelt component A suite of three computer programs for the calculation of snowmelt is being developed, two of which are based on the standard degree-day and energy budget methods. The third is intended for use when changes in the temperature and structure of the snowpack have a significant effect on the flow of water within it, and is based on two simple equations for the flow of mass and energy within the snowpack. The flow of water is described by the Richards' equation for flow in a saturated or unsaturated porous medium (as given earlier) and the flow of heat by the heat conduction equation

$$\frac{\partial}{\partial z}\left(\frac{K\partial T}{\partial z}\right) = \rho\, c_p\, \frac{\partial T}{\partial t}$$

where K is thermal conductivity, and ρ, c_p are the density and specific heat of the medium respectively. This simplified description does not take the transfer of heat and water vapour by convection directly into account but the effect of these processes can be included implicitly by a suitable choice of 'effective' values for the thermal and hydraulic conductivities which appear in the two basic equations. The hydraulic and thermal properties of the snow are defined by empirical equations in terms of its average density, grain size, water content and temperature.

The equations for flow of heat and water within the snowpack are linked by their internal source terms, since melting of the matrix provides both a water source and a latent heat sink. Two simplified semi-empirical equations are used to complete the set of relations required to define temperature and water content distributions. These are (i) an equation relating the equilibrium temperature of wet snow to the water content and average grain size, and (ii) an equation relating changes in density and average grain size to the amount of melting and refreezing of the matrix.

The upper boundary conditions are calculated from meteorological data and it is assumed that all the energy from solar radiation is absorbed in the top layer of the snowpack. The rates of evaporation of water and convective transfer of heat are calculated from the wind speed and temperature gradient, whilst the lower boundary conditions are given by another part of the model which calculates infiltration into the soil.

Real-time forecasting of hydrological variables

Real-time forecasts of measures of water quantity and quality are fundamental to the short-term operation of a water resource system. Models such as those described above possess two important disadvantages for real-time use. Firstly, they may demand considerable computer resources and a complicated initial procedure for the estimation of their parameters; secondly, they cannot explicitly correct their forecasts in real-time as telemetered information reveals the magnitude of errors. Consequently, the aim has been to develop real-time hydrological models which incorporate the following features:

(i) The models should be adaptive in the sense that they should be capable of making use of information from new measurements to update their forecasts and parameter estimates;

(ii) The models should explicitly take account of errors of measurement of hydrological variables used in making forecasts;

(iii) The models should provide a measure of error associated with their forecasts and parameter estimates;

(iv) The models should be capable of implementation on small, mini or micro computers with minimal storage facilities.

The requirement for frequent updating of forecasts, and of model parameters, is a characteristic of many problems in control engineering, such as that of rocket guidance; this discipline has developed its own techniques, some of which find direct application in real-time streamflow forecasting once the difficulties of terminology have been overcome. The behaviour, or 'state' of the system at any time k must be represented by a vector of state variables x_k with elements which may or may not be directly observable; if, say, x_k contains n elements, then the model is defined in an 'n-dimensional state space'. Many linear hydrological models can then be described by a 'system equation'

$$x_k = \Phi\, x_{k-1} + \Lambda\, u_k + \Gamma\, w_k$$

where x_k is the vector of state variables at time k, u_k is a vector of forcing inputs (such as precipitation) and w_k is a 'noise' term expressing the fact that the system equation will be an imperfect description of the more complex reality; Φ, Λ and Γ are matrices of appropriate dimension. Since the elements of x_k may not be directly observable, an 'observation equation' is required which relates the vector y_k of what is measured at time k (such as streamflow, dissolved oxygen, electrical conductivity) to the vector of state variables x_k. Such an equation could be

$$y_k = M\, x_k + v_k$$

where v_k is a vector of noise variables expressing the fact that the observations y_k are likely to be subject to random errors of measurement. Thus, a system's behaviour can be described by a 'system equation' and an 'observation equation' (which, in the above case, are both linear, but which are easily generalised to non-linear cases). The Kalman filter, an elegant technique developed by the control engineer R E Kalman, then provides a method for obtaining estimates of $\hat{x}\,(k+1\,|\,k)$ of the state vector at time $k+1$, given all observations up to time k, (and similarly $\hat{x}(k+2|k)$, $\hat{x}(k+3|k)$ . . . etc) and for 'updating' the estimate of the state vector as new observations become available by calculating $\hat{x}(k+1|k+1)$. When the matrices Φ, Λ, Γ are known, the Kalman filter therefore provides a recursive estimation for the state vector x_k, furnishing estimates of present and future values of the hydrological state variables based on imprecise model dynamics and noise measurements. However, the matrices Φ and Γ contain parameters which are generally not known, and which must be estimated in some way. The two applications of this approach to hydrological systems have tackled this problem in different ways.

The first application considered a very simple catchment response which assumed that the flow in a river at time t, namely $q \equiv q(t)$, is some power of the catchment storage $S \equiv S(t)$, as defined by the relation

$$q = KS^n, K > 0; n > 0$$

Combining this with the equation of continuity gives the deterministic catchment response model

$$\frac{dq}{dt} = a(cu' - q)q^b$$

where u' is effective rainfall, and a,b,c are three parameters. At time $t \equiv t_k$ it was assumed that a function $h(t_k) \equiv h_k$ was known which satisfied

$$\frac{dh_k}{dt} = a(cu' - h_k)h_k^b \qquad t_k \leqslant t < t_{k+1}$$

with $h_k(t_k) = q_k$. The true but not-yet-known flow at time t_{k+1}, namely q_{k+1}, will deviate from the extrapolated estimate $h_k(t_{k+})$ by a quantity v_{k+1} (Figure 6), so that

$$q_{k+1} = h_k(t_{k+}) + v_{k+1}$$

The similarity of the above with the measurement equation is evident, although it now describes the model dynamics which are non-linear and continuous in time. The missing system equation is introduced simply by assuming the state vector x_k to comprise the parameter set $[\ a,b,c\ ]$, and the assumption that the

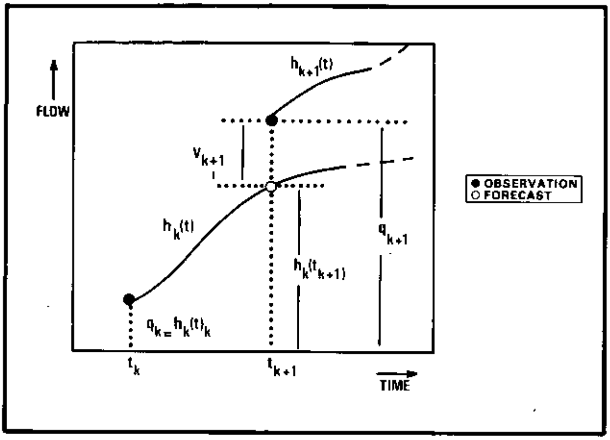


Figure 6. *Change of forecast streamflow function at an observation*

parameters do not vary over time is obtained by setting the system noise to zero. The extended Kalman-filter algorithm now provides an approximate solution to this stochastic non-linear estimation and forecasting problem. In the present context, where non-linearities occur only in the measurement equation, it derives simply from the linear Kalman filter after linearising the measurement equation about the current estimate of x_k by a Taylor expansion.

The second application considered the problem of real-time channel flow routing. A very simple model was chosen in which the flow q_k at node n at time k was assumed to be linearly related to the flow at the same node and at the previous node at the previous time instant as follows:

$$q_k^n = \theta q_{k-1}^n + (1 - \theta)\, q_{k-1}^n + \theta\, i_k^n$$

where the quantities i_k^n denote tributary and other lateral inflows. This linear discrete-time model may be readily written in state-space form, where the states comprise the quantities q_k^n at the various nodes. Measurements of flow at any of the nodes are incorporated via the measurement equation. The unknown parameter θ occurs in the matrices Φ and Λ, and although the model is linear, the simultaneous estimation of states and parameters therefore constitutes a non-linear estimation problem. The solution adopted employs a Bayesian formulation for the parameter estimation problem in which the estimation of the state vector for a fixed parameter is performed through the linear Kalman filter. The procedure assumes that the parameter θ will vary over time, and its evolution in time is used to identify a functional relationship between the model parameter and channel flow magnitude (Figure 7). This Bayesian-Kalman filter procedure thus provides a novel approach to the identification of a non-linear system; a non-linear functional relation between the parameter θ and channel flow was successfully identified from simulated data.

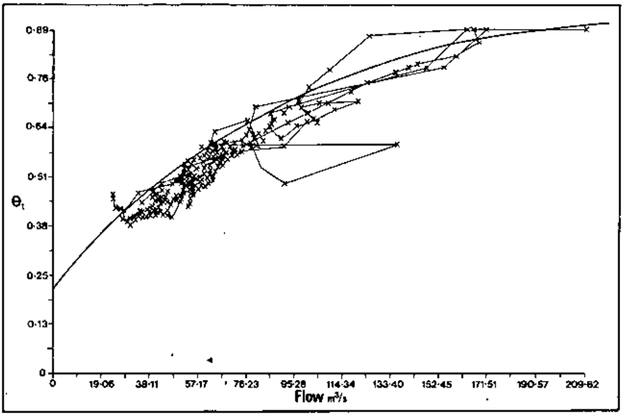


Figure 7. *Estimated values of the parameter θ obtained from the synthetic data plotted against generated flows, true function indicated by the curve*

Non-linear modelling of hydrological time series

Whilst much of the classical time series analysis assumes a linear structure for the postulated processes, this assumption is adopted for simplicity and not because of universal validity. Non-linearity of hydrological time series can be particularly pronounced, and it is therefore important to incorporate such features into models for forecasting. Figure 8 shows the average flow over each day for the River Irfon at Abernant using only days in the Januarys of successive years. Here values of the flow on each day are plotted against the flow on the preceding day; the graph suggests the formulation of a stochastic model

$$x_t = f(x_{t-1}) + \epsilon_t$$

where ϵ_t is a random forcing quantity, not necessarily

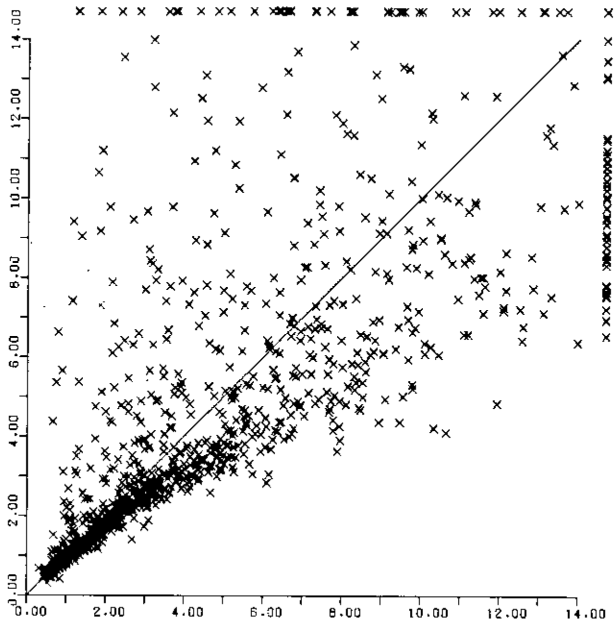


Figure 8. *Average flow for River Irfon at Abernant*

independent over time, and $f(.)$ represents the non-linear function discernible in Figure 8. Sequences of synthetic data were generated using a model of this form fitted to the historical record, and these sequences were found to compare favourably with those generated by other models. In particular, it can be shown that if $f(.)$ can be represented as

$$f(x) = x - bx^c + \dots$$

near $x = 0$, and if the random input is zero for a time, then the simulated flows, x_t, behave as $(bt(c-1) + k)^{-1/(c-1)}$. Thus the model allows for an inverse power decay of x_t, whereas other models have implied exponential decays of low flows which have not agreed well with observed streamflow recession behaviour. Further investigation is to be made of the use of non-linear stochastic models.

Rationalisation of the UK raingauge network

In August 1976, a study of the UK raingauge network of daily and monthly gauges began under contract to the Department of the Environment. The objective is to rationalize the present network by first establishing the requirements of users of rainfall data and then re-designing the network to meet these requirements more efficiently.

Work to date is in two phases. Under Phase I of the study (see IH Report 40), user requirements for rainfall data within the UK were surveyed extensively; principal users were the water and civil engineering industries, agriculture, meteorology, public utilities, law, insurance and health bodies. Users were requested to specify (i) whether their requirement was for point or areal estimates of rainfall; (ii) the time interval for which total rainfall was required; (iii) the accuracy of the required estimate, expressed either as a percentage or as an absolute error that should be exceeded only with small frequency, usually 5%.

Methods for evaluating the performance of the present UK network were of two kinds depending on whether a measured or estimated rainfall was used directly to decide upon a course of action, or indirectly, such as when the measured or estimated rainfall was used to predict a streamflow hydrograph by means of some model of basin hydrological response. Techniques for the direct method of evaluating network adequacy used essentially the following steps:

(i) An area was selected within the UK containing several hundred daily-read raingauges;

(ii) A spatial correlation function was fitted describing the decay of correlation with distance within the area;

(iii) The fitted correlation function was used to derive optimal weighting procedures for estimating point and areal rainfall over various durations.

Two areas were selected, one in the east of England containing approximately 670 gauges, and one in the north of England containing approximately 1150 gauges. Three categories of daily data (consisting of days with different depths of rainfall) were analysed in addition to monthly and annual data. A typical plot of correlation against distance for monthly rainfall is shown in Figure 9. Once correlation functions had been fitted for these areas, estimation errors (expressed as the root mean square error divided by the standard deviation of the rainfall quantity x 100%) were then

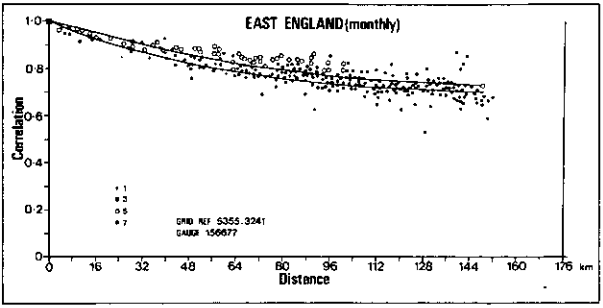


Figure 9. *Sample correlations of monthly total rainfalls in eastern England. Different symbols are used according to the relative orientation of each pair of gauges. The fitted correlation function is shown for two orthogonal directions.*

derived for (i) an optimal point interpolation procedure which assumed that the network was arranged on a triangular grid and which used three gauges to interpolate to a point; (ii) an areal averaging procedure which assumed that the network was arranged on a square lattice and that the area itself was square. Relations between the estimation error and the spacing of raingauges on a regular grid could then be specified; by entering these relations with the required percentage root mean square error, the gauge spacings necessary to meet particular user requirements could then be established. An example of one of these relationships is given in Figure 10 for point monthly rainfall. These required spacings were then compared with the map of observed average inter-gauge distances to determine if various user requirements were satisfied; with some exceptions, this was mainly found not to be the case. A possible explanation is that users had overspecified their requirements.

Because many decision-making processes using rainfall data are informal and difficult to express in quantitative terms, the use of indirect methods was limited to (i) a study of the effect of daily raingauge density on the accuracy of streamflow prediction using a rainfall-runoff model; (ii) a study of the effect of density and configuration of networks of telemetering raingauges on the accuracy of short-term flow forecasts. For the first study, six catchments were selected from within the UK ranging in area from about 225 km^2 to 500 km^2, and a lumped rainfall-runoff model was fitted using the well-documented Constrained Linear Systems fitting procedure. By fixing

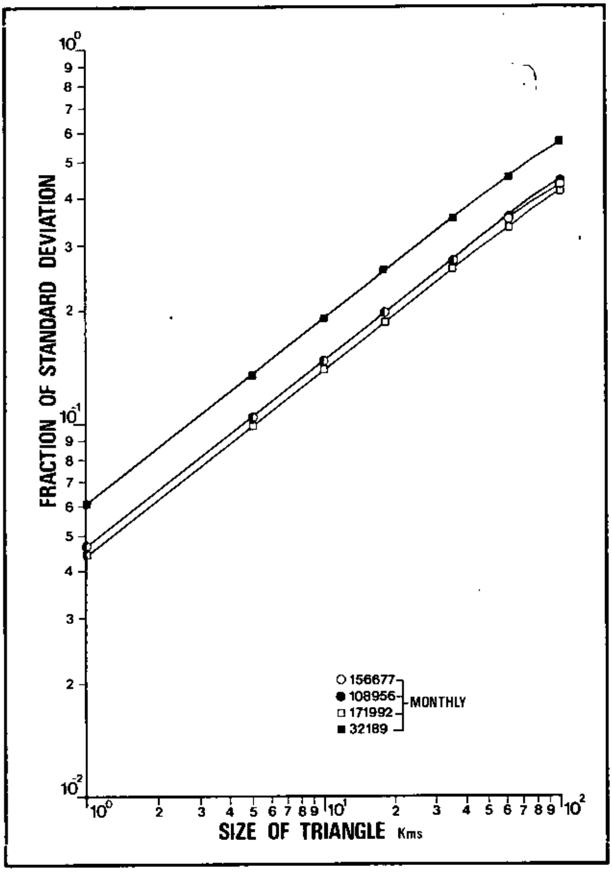


Figure 10. *Interpolation error to centre of equilateral triangle: monthly totals, eastern and northern England*

the model parameters, and observing the effect of network density on the accuracy of flow prediction, it was found that this accuracy was limited by network density in some catchments but not in others. In the second study, a 'black-box' model was fitted using half-hourly rainfall and runoff data from the Hirnant subcatchment in the River Dee Basin; both spatially-averaged and spatially-distributed rainfall were used. The tentative conclusions were that (i) a rainfall forcing function that is more highly correlated with streamflow can result through using a sub-set of gauges rather than the entire network; (ii) one or two gauges should be adequate for real-time flow forecasting on a small catchment, and their siting should reflect the area contributing to the rising limb and peak of the hydrograph.

After completion of Phase I of the study, the Wessex Water Authority (WWA) agreed to participate with the Meteorological Office (MO) and the Institute in a case study to redesign the network for the WWA area; this phase of the study (Phase II) is now in progress. It is hoped that the approach used for the WWA area will be subsequently applied to the rationalisation of other Water Authority networks.

Work on Phase II of the study began with a survey of user requirements, the major users being WWA, MO and MAFF (ADAS). Where possible, accuracy requirements have been regionally delineated, and have been established by analysing each rainfall use in as much detail as possible. These could again be classified as either direct or indirect.

The spatial correlation structure of rainfall over the WWA area has been established for each of a series of squares 5 km × 5 km using gauges lying within a surrounding 35 km × 35 km area. The correlation function used was of the form:

$$\rho(u,v) = a + (1 - a - \epsilon) exp\left\{-b \left[u + c_1 v)^2 + (c_2 v)^2\right]^{1/2}\right\}$$
$$u,v \neq 0$$

where u and v describe the x and y differences between gauge co-ordinates, and b, c_1, c_2, ϵ are parameters. An optimal point interpolation procedure has been developed whereby any number of irregularly-spaced gauges can be used and the interpolation error quantified. This procedure has been used to map interpolation error over the WWA area on a 1 km grid for the present network; this has been carried out for monthly rainfall and three categories of daily rainfall. An example of such a map is given in Figure 11 for monthly rainfall. By comparing these maps with the accuracy requirements of users, areas of deficient accuracy can be defined. Empirical interpolation at an ungauged point is frequently carried out by simply using the recorded rainfall at a nearby gauge; the accuracy of this technique has been compared with that of the optimal procedure, illustrating the higher accuracy obtained from the latter.

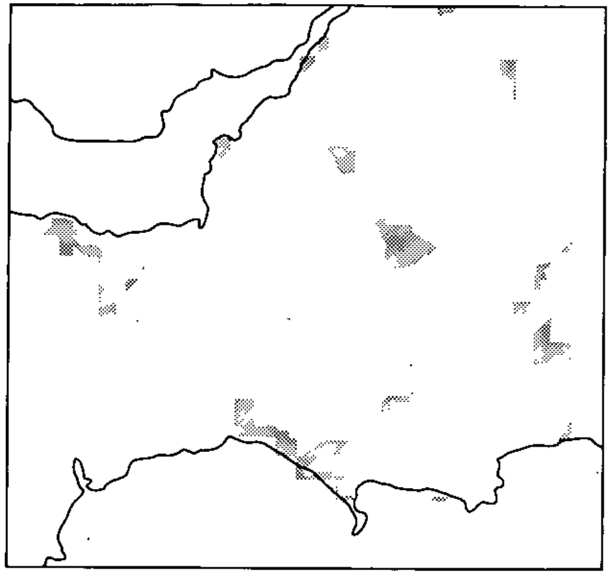


Figure 11. *Regions (shaded) for which the rise of optimal interpolation is greater than 6·5 mm for monthly rainfall totals, based on the existing network of all known gauges (379 in all)*

A procedure for quantifying the accuracy of areal rainfall estimates has also been developed which will work for any arbitrary shape of area and any irregular configuration of gauges. The procedure has been applied to a number of regions within WWA where specific areal accuracies are required.

Work is currently in progress on the final design of the WWA network; three possible networks of approximately 75, 200 and 300 daily-read gauges are being considered. These networks have been arrived at by first identifying a basic network of regularly distributed gauges (using existing gauges where possible), and then adding additional gauges to meet specific regional requirements to maintain a sufficient number of gauges with long records and to incorporate a sufficient number of high quality sites.

Catchment studies

The Plynlimon catchments

1978 is the end of the ten-year period originally allotted for the Plynlimon project on the headwaters of the rivers Severn and Wye. The initial intention was that ten years of records of rainfall and runoff, climatic variables and soil moisture measurements would be collected and analysed to permit conclusions to be drawn regarding the effect of forestry and grassland management practices on water yield and flood behaviour of the two catchments.

In the event, the installation and proving of the instrument networks took longer than anticipated. Analyses of the data collected so far (some six years of records at present) have been undertaken and conclusions published (Anon, 1977) concerning water yield, with the proviso that a longer run of data may lead to adjustment in the figures.

The techniques of making measurements have been and still are under continual review and improvement. This aspect of the work arouses considerable interest with visiting hydrologists at all levels. Initially, measurements were heavily dependent on field observers. Early attempts to use automatic methods had limited success because of the environment but the development of the Microdata logger opened the way both for automatic recording and computer processing of field data. For example, the original storage rain gauge totals from 39 sites throughout the catchments were distributed in time and amount by the results obtained from six Dines chart recorders; although the storage gauge network remains, the distribution of the catch is now based on the results obtained from Rimco tipping bucket gauges recording on magnetic tape. Likewise, discharges through each of the eight gauging structures are calculated using levels logged at five-minute intervals on magnetic tape. The most significant benefit is of course the reduction in manpower involved in running manual systems which thus frees field staff for other work, a particularly important advantage in the present research climate.

At the time of the last Research Report the gauging structures were being calibrated using multipoint current metering in the approach section. This work was completed and the calculations made by the Hydraulics Research Station. Differences between the field calibrations and theoretical values at the Hafren flume are still awaiting resolution. The current-metering calibrations spanned the period of the 1976 drought.

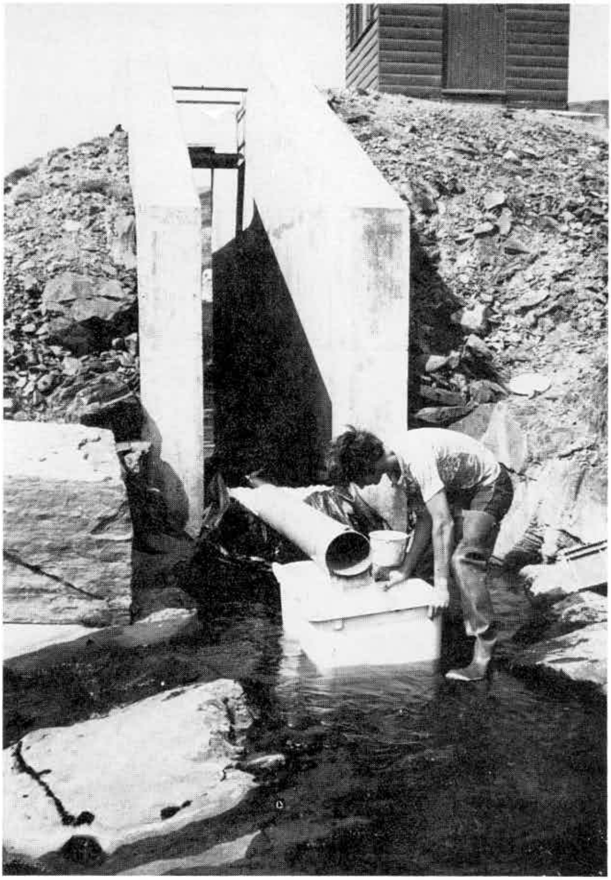


Figure 12. *Volumetric low flow gauging, August 1976*

Stream levels fell below tapping points and were so low that volumetric gaugings were undertaken at all structures. These were particularly valuable since BS 3680: 1974, Part 4c Sect 551 defines the minimum lower limit of head below which the theoretical rating should not be used. At and below these levels current metering is not practicable and minor surface deformities have a proportionally greater effect on discharge. Table 2 illustrates for each flume the minimum lower limit of head and the percentage of time the stage was in stated bands during 1975.

An observed difference between water levels in the flume and in the well, possibly attributable to aeration, has been reported in IH Report No. 42; the problem has not yet been resolved.

Flume	Minimum limit of head, mm	% time in stated band		
		0–100 mm	100–200 mm	200–300 mm
Severn trapezoidal	212	6·4	31·7	30·5
Tanllwyth	183	45·2	43·1	7·1
Hore	343	0·0	50·6	26·1
Iago	183	38·6	41·2	8·0
Gwy	275	0·0	36·0	36·4
Cyff	237	0·0	38·5	22·1

Table 2. *Plynlimon flume performance during 1975.*

Snowfall The problem of measuring snowfall is hampered by its ephemeral nature and spatial variability. In the last two years the techniques of using both stereo-photogrammetry and the ground level raingauges covered with artificial grass over a permeable matting referred to in the last report have been tested and abandoned. There are several reasons for this. First, it has proved impossible to devise a simple way of correcting the storage gauge totals for periods of snowfall. Secondly, adequate snowfall measurement requires a network of sites even denser than that for the existing raingauges plus a combination of instruments at each site measuring specific components of the snow balance—prohibitively expensive in equipment and manpower. Thirdly, it is apparent that the catches recorded by the storage gauges during snow periods can be distorted by an order of magnitude. With stereophotogrammetry, the four sites installed were obviously a quite inadequate sample to cover the variation in snow depth throughout the whole catchment; the need to walk the site to collect cores for snow density negates any advantages of remote sensing from a few points only.

The current solution to the problem is that forty-one key sites have been identified on a domain basis within the two catchments. A depth and coring routine now operates at each of these sites during snowfall which gives a reasonable measure of snow pack storage although an inadequate prediction of melt water input.

Remote sensing

Behind much of the Institute's research work is the need to extrapolate from localised measurements of water quantity and movement to larger areas. It is pertinent therefore to follow closely the state of the art in the rapidly expanding remote sensing technology. At present, remote sensing can do little towards measuring directly sub-surface variations in the water cycle but where surface changes occur, these can often be most easily quantified from an aerial viewpoint. Satellite data are now widely used for the observation of large scale climatic variation and considerable potential exists for interpolating between ground meteorological observations with the aid of various types of remotely-sensed data.

When a record of static or slowly changing features is required, such as river catchment area, and suitable remotely-sensed data taken within the last few years are likely to suffice. In this category LANDSAT imagery has proved to be very useful for the provision of topographic, land use and limited surface geological information for overseas water resources studies where adequate maps have not been available. However, for the sensing of dynamic hydrological features such as flood water extent, the timing of the aerial observations is most important. In the UK especially, such temporally dependent observations are often hampered by cloud cover which can be regarded as one of the main problems facing the user of remotely-sensed data. By sensing at microwave (millimetre-metre) wavelengths, cloud and atmospheric haze can be successfully penetrated and all-weather, day or night sensing becomes possible. Such data are not yet widely used because from satellite altitudes they suffer from poor resolution and from aircraft altitudes they are expensive to obtain. Having accepted the real problem which cloud cover poses to remote sensing, two approaches have been adopted in an attempt to satisfy some present and future remote sensing data requirements. Firstly, inexpensive light aircraft are used to take observations at very short notice so that full advantage can be taken of favourable weather conditions and secondly, the experience gained from the involvement in the joint European TELLUS project should place IH in a favourable position to make use of future microwave data when they become readily available.

Light aircraft facility

Low cost data collection is achieved by hiring standard aircraft only when required, so eliminating costly standby fees. Any of the widely available Cessna 172 light aircraft are used since all equipment is designed to be fully interchangeable. An aircraft can usually be obtained locally at very short notice or, where more efficient, it may be hired from an airfield which is close to the point of data collection. Figure 13 shows the aircraft fitted with a baggage door which has been modified to allow vertical aerial photographs to be taken. A fully automatic 35 mm camera with large film magazine is used and if necessary, overlapping of photographs along a flight line can be achieved by intervalometer control of the camera shutter. 35 mm format film is used to keep operational costs as low as possible and this has proved to be satisfactory for most

Figure 13. *Cessna 172 with modified baggage door*

of our local requirements. A wide range of film types and filter combinations is available but natural colour and colour infrared film appear to be the most versatile for recording ground surface and water related features.

The system has been used to map such features as stream and field drainage networks, urban growth and impervious surface contributing area types, surface geology exposures, tidal water effluent sources, and effluent dispersal through dye tracing and river flooding. The virtues of the low cost system were clearly demonstrated in its application to flood mapping where extension of the sensing range into the near infrared region proved to be particularly useful.

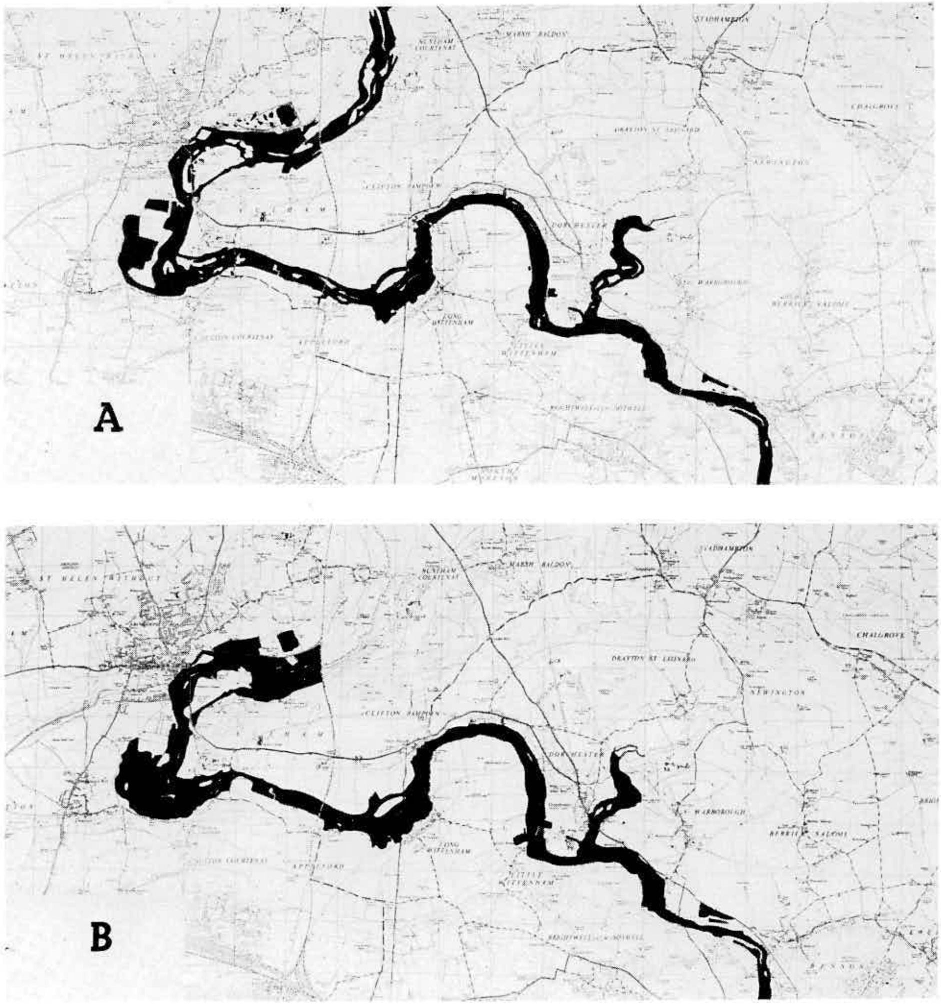
River Thames flood mapping

Water Authorities now have a statutory requirement to record the extent of major flooding and this is often costly especially when ground based mapping methods are used. Accurate mapping of flood extent is possible using light aircraft photography which can be considerably cheaper. Rainfall in the Wallingford region of the mid-Thames basin was above average for January 1977 whilst for February 1977 the monthly rainfall total of 86 mm was almost three times the average for that month. On 18th, 19th and 20th February over 10 mm of rain per day was recorded at Wallingford and as a result, extensive inundation of the river flood plain occured to approximately the 1-in-20 year level. From ground observations, the flood peak appeared to be imminent on 23rd February although in fact the highest level at Wallingford was not reached until 25th February. As weather conditions were favourable, it was decided to record the extent of the flooding from the air. The time taken between making this decision and taking the first aerial photographs of the flood was just over two hours, during which time the availability of an aircraft was checked, equipment was transported 24 km to the airfield, the modified baggage door with camera was fitted to the aircraft and the aircraft was flown back 19 km to the flood site. Both vertical and oblique colour photographs were taken of the flooded river along a reach of about 43 km between Pangbourne and Abingdon.

The main problems with extracting flood information from this type of record is that there can never be certainty that the river hydrograph is at its peak at the time of photography—as was clearly the case in this instance. Even if the time of flood peak could be predicted accurately, the photographic record would only catch the peak at one point on the river at any given time. However, additional overflights were made using colour infrared photography to evaluate the hypothesis that the presence of flood water causes a physiological change in the leaf structure of inundated vegetation which in turn results in a lowering of the plant's near-infrared reflectance. This effect may persist for several days after the recession of the flood water and is recorded on colour infrared film as a change from the magenta-red colour of healthy green vegetation to the distinctive blue of stressed vegetation.

Colour infrared aerial photographs were taken of the Pangbourne-Abingdon reach on 2nd and 4th March (five and seven days after the flood peak) for analysis without reference to the near-flood-peak photographs; there resulted a line of estimated maximum flood extent using only the post-flood colour infrared images (see Figure 14a). When this had been completed, the same interpreter constructed the flood line as recorded on the near-peak photographs (see Figure 14b). Comparison of the two flooded boundaries shows some discrepancies, but some of these can almost certainly be attributed to the fact that the water level continued to rise after the completion of near-peak photography and that the post-flood infrared photographs would tend to record the maximum flood level throughout the whole 27 mile stretch of river. Ground knowledge of the local flood level would certainly support this, but further work is required to establish for how long soil waterlogging must occur in order to produce noticeable changes in near infrared reflectance of the vegetation and whether the period of waterlogging affects the persistence of this change. The total cost of producing the flood extent map was less than £300, ie. £6 per km of river surveyed, proving that light aircraft photographs can supply an aerial record of a dynamic hydrological event very cheaply and at very short notice.

Figure 14. *River Thames flood of February 1977 (a) determined from true colour aerial photographs (b) determined from colour infra-red aerial photographs five days after peak flow*



TELLUS heat capacity mapping mission

The TELLUS project is a joint European experiment co-ordinated by the Joint Research Centre at Ispra, Italy, for the analysis of data from the NASA Explorer-A satellite launched in April 1978. IH is working with Leeds and Reading Universities on the collection of ground information from test sites at Grendon Underwood, Newbury and the Vale of York, and subsequently on the analysis of both satellite and ground data to determine among other things whether surface soil moisture and evaporation can be estimated from satellite altitudes. Experience gained from this project will aid the planning of future satellite systems and will improve methods of utilizing satellite data.

The Explorer-A satellite has a planned life of 12–18 months and carries imaging sensors operating in thermal infrared and visible wavebands. The thermal 10·5–12·5 micron sensor, which has a ground resolution of 500 × 500 metres, allows the measurement of ground surface radiometric temperature whilst the 0·5–1·1 micron sensor provides information on surface albedo. Satellite overpasses of the UK occur at 02.30 a.m. and 13.30 p.m. of every eighth day.

Two computer-based models are being used to relate day-night soil surface temperature differences to soil surface moisture content; one model is for bare soil and one for short grass. Both simulate the changes in the energy balance of the soil surface over the course of a day; given some rather severe assumptions, these changes may then be used to estimate the thermal inertia and hence the moisture of the soil surface. In addition, the cumulative daily evaporation can also be estimated.

Both models have been tested using data from the Grendon Underwood test site which were gathered during a joint flight experiment in September 1977. An aircraft equipped with sensors operating in the same wavebands as those of the Explorer-A satellite took night-time thermal and day-time thermal and visible radiation measurements of the test site from an altitude of 1000 metres; concurrent with the overflights, surface meteorological, soil moisture and radiometric temperature measurements were made. During the operational life of the satellite, further ground and low level aerial data will be collected in order to test the accuracy of the models and to assess the usefulness of the satellite data.

Nutrient studies

Increasing concern over levels of nitrogen, especially nitrate-N, in potable water and the potential effect on health, has prompted the Ministry of Agriculture, Fisheries and Food to instigate a series of investigations into the ways in which nitrogen is reaching water supplies. Three of these investigations, two at Plynlimon and one at Shenley Brook End, are being carried out by the Institute in collaboration with the Agricultural Development and Advisory Service.

Water sampling in the Wye and Severn catchments at Plynlimon

Two pairs of North Hants water samplers, one sampling every eight hours and the other every half-hour during periods of high flow only, were installed at the Cefn Brwyn weir on the Wye and at the Severn trapezoidal flume in July 1976. These water samples are analysed at MAFF's Experimental Husbandry Farm, Trawscoed, to give daily and, at high flows, hourly estimates of ammonium-N, nitrate-N, total N, phosphorus and potassium concentrations. This information is then used to determine:

(i) The natural levels of nutrient concentrations in streams from uplands and the seasonal variation in these concentration levels.

(ii) The effects of high flow conditions on the levels of nutrient concentrations.

(iii) The differences in nutrient concentrations in streams from grassland and forested catchments.

So far, it is clear that the mean nutrient concentrations in both streams are very low (rarely exceeding 1 mg/ l), though they tend to increase with increasing flow level. This increase is particularly evident during storm events following a hot dry spell. The proportional contributions to this increase from the levels of nutrient concentration in the rainfall and from nutrient leaching from the soil profile have yet to be determined.

The nitrate-N concentration in the stream draining the forested catchment is consistently higher than that in the stream from the grassed catchment, a phenomenon for which as yet there is no satisfactory explanation.

Effects of improved grassland cultivation at Plynlimon

The first proposal for this study was to compare two of the sub-catchments in the Wye catchment at Plynlimon before, during and after improvement of the vegetation of one sub-catchment, by monitoring any differences in water quantity and quality. Coupled with this it was proposed to carry out a smaller experiment in which the processes governing the movement of water and nutrients over and through the soil profile would be studied using two 'natural' lysimeters, one of which would be under 'improved' vegetation. Unfortunately it was found that the cost of the sub-catchment experiment was prohibitive and it was decided to carry out the lysimeter study alone.

The experimental site consists of an area of land of approximately 2½ hectares in the Nant Iago sub-catchment. The land is on a slope of one in ten and is rough pasture on peat over boulder clay. When the site was initially inspected by ADAS it was decided that it should be properly drained before any improvement could be carried out. Consequently a series of back-filled tile drains at 10 metre intervals was installed during the summer of 1977. The site was then divided into two halves and a 10 m by 10 m 'natural' lysimeter constructed within the drainage scheme in each half. The sides of the lysimeters were sealed to a depth of 1½ metres using plastic sheeting concreted into the underlying impermeable boulder clay which provides the bottom seal.

Both the surface and sub-surface discharges from each of the lysimeters are measured and water samples taken on a proportional volume basis. The site is equipped with recording rain gauges and a weekly-read storage gauge which also acts as a rainfall sampler. Each lysimeter is equipped with weekly-read neutron access tubes and a series of tubes at different depths which facilitate the collection of water samples from the peat. Peat core samples have been taken at different depths and at different points in the site and have been analysed at Trawscoed to determine the natural nutrient content of the peat.

Measurements were started in October 1977 and the initial data are now being analysed in detail. The improvement to one half of the plot was carried out during the spring of 1978. This improvement consisted of liming, surface skimming, re-seeding and an annual application of fertilizer according to ADAS recommendations. Subsequently, the improved half of the site, which is fenced off, will be subjected to the ADAS recommended level of grazing management to ensure that the hydrological and nutrient data obtained are representative of the 'improved grassland' situation.

Since both lysimeters are identical in soil type, slope, rainfall and weather conditions, any differences in nutrient concentrations in the surface and sub-surface discharge can be attributed to the effects of improved grazing.

The effects of agricultural practices on water quality at Shenley Brook End

Here the main aim of the joint IH/ ADAS study is to investigate nutrient losses in streamflow and their relation to agricultural practices including fertilizer application in an intensively-farmed area.

The location chosen for this study was the catchment at Shenley Brook End in Milton Keynes, Buckinghamshire. This catchment of 172 hectares was instrumented by the Institute in 1971 to measure areal rainfall, runoff and to estimate areal evaporation. It consists of 11% woodland, 22% arable land and 67% intensively managed grassland.

A North Hants water sampler extracting water samples every eight hours was installed at Shenley Brook End in January 1978. These samples are analysed by MAFF, Reading, to give daily nitrate-N plus weekly ammonium-N, phosphorus, potassium, magnesium and calcium. Another North Hants sampler is to be installed to collect a sample every half hour during storm events. Rainfall samples are also to be analysed for nutrient concentrations.

These results, together with the areal estimates of rainfall and runoff, are to be used to determine the seasonal pattern of nutrient concentrations and the total amounts transported in the stream. In conjunction with this, ADAS are to request the farmers on whose lands the catchment lies to keep diaries of fertilizer applications and other agricultural practices in order to determine what effects these practices have on the levels of nutrient concentrations in the stream.

Hydrological Processes

Evaporation

Physical controls of evaporation

The long-term experiment on physical controls of evaporation at the Thetford Forest site is now drawing to a close. Refinements in measuring techniques have been made and, at both the main site within the forest and at a second site nearer the edge, many days' measurements of the energy budget and the Bowen ratio have been recorded using the thermometer interchange system shown in Figure 15. Such measurements are used in the calculation of evaporation from the forest for each hour of measurement, as shown in Figure 16 for a typical day when the forest canopy was dry and transpiration was occurring. Figure 17 shows the results obtained for a day when the forest canopy was wet during and after rainfall; under these circumstances, the evaporation of intercepted water influenced the amount of evaporative loss. On dry days the surface resistance was large and only 28 per cent of the net radiation was used for evaporation, whereas on the wet days, the surface resistance was zero and the evaporation process used much more energy than that provided by net radiation alone.

A team from Edinburgh University, under the direction of Professor P G Jarvis, has also been working at the main Thetford site. His group has been measuring the carbon dioxide gradients simultaneously with the Institute's micrometeorological readings and both sets of measurements have been combined to calculate the rate of photosynthesis of the forest. The Edinburgh University team has also measured stomatal resistance, leaf water potential and C^{14} uptakeof individual shoots from which it hopes to develop models describing stomatal response to the uptake of CO_2 and its relation to environmental variables.

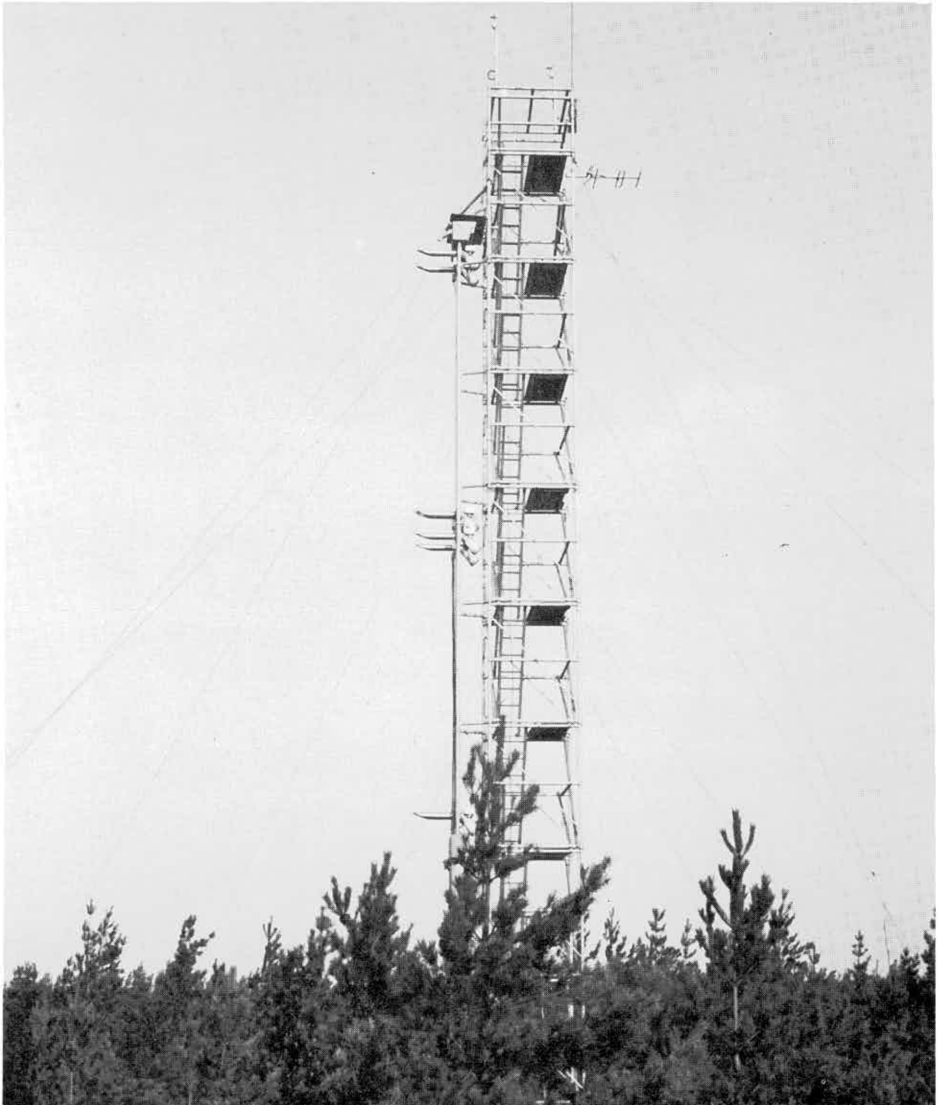


Figure 15. *An instrument tower supporting the thermometer interchange system to provide accurate measurements of the temperature and humidity gradients*

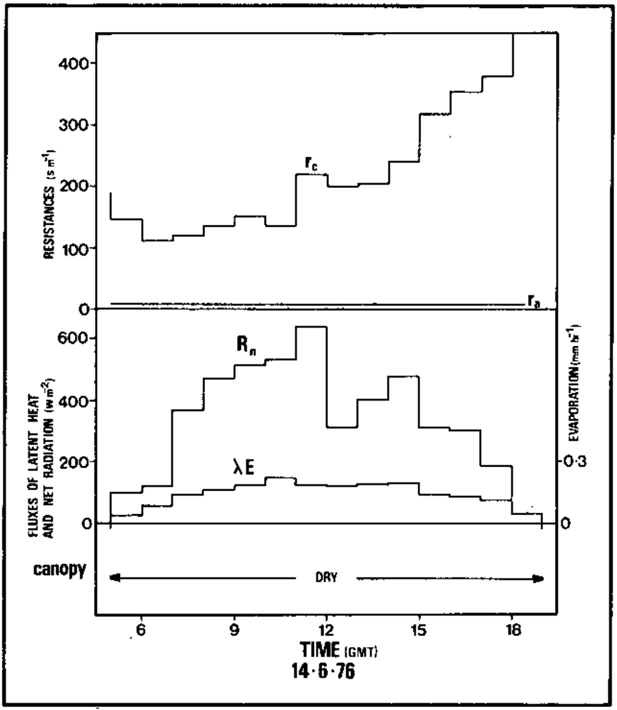


Figure 16. *Fluxes of net radiation, R_n, and latent heat, λE, (and the equivalent evaporation) during a typical dry summer day over Thetford Forest. The two resistances, the canopy resistance, r_c, and the aerodynamic resistance, r_a, which control the evaporation*

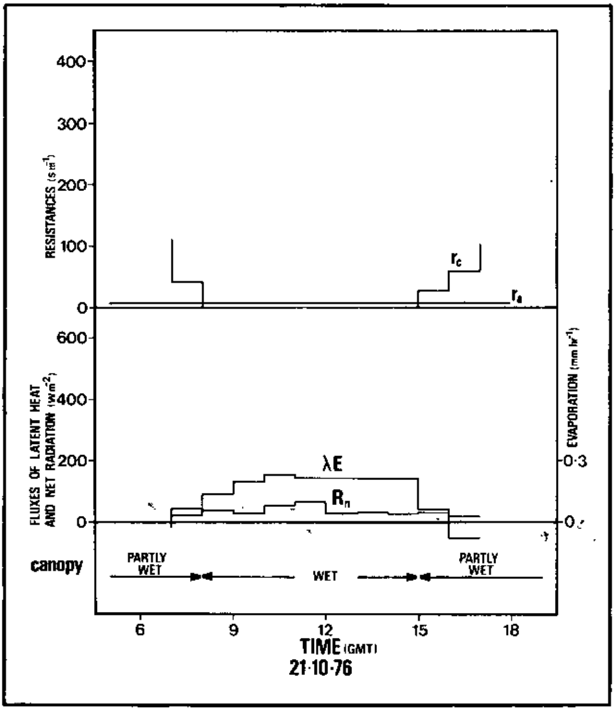


Figure 17. *Fluxes of net radiation, R_n, and latent heat, λE, (and the equivalent evaporation) during a day when the forest canopy was wetted by rain. The two resistances, the canopy resistance, r_c, and the aerodynamic resistance, r_a, which control the rate of evaporation*

Eddy correlation studies

The Institute's work over the last decade in Plynlimon and Thetford has underlined the fact that evaporation from the earth's surface is more variable than was at one time thought. This variability, which is primarily a consequence of the control asserted on the evaporation process by the vegetation at the surface, is more obvious when changing from one vegetation type to the next (e.g. from grassland to forest), and in conditions of drought, when the moisture available in the soil is greatly reduced. Both of these situations are important hydrologically; the first, because changes in vegetation cover commonly occur in water yielding catchments; the second, because it is in just such drought conditions that accurate knowledge of the evaporative loss is most important. If the accuracy with which available water resources can be measured is to increase at a rate consistent with the growing demand for water, it is necessary to establish, quantify and understand this variability in evaporation rate.

A great deal of valuable research has been carried out using existing evaporation measurement techniques, such as the energy budget/ Bowen ratio method, but the work is time-consuming and expensive in terms of man hours and equipment costs. Studies of spatial variability are only feasible if the measurement of evaporation can be undertaken at many sites and over different vegetation types in an essentially routine way. With this in mind, IH is trying to measure and understand the process of water vapour transfer by near-surface, atmospheric turbulence, one of the practical objectives being the eventual development of a device capable of providing routine measurements of evaporation using the 'eddy correlation' technique.

In the eddy correlation technique the fluctuating components of atmospheric humidity and windspeed (normal to the surface) are measured at high frequency, their product calculated and accumulated to give the total flux. The method has only recently become feasible at reasonable cost with the advent of cheap, numerical processing electronics (microprocessors). For hydrological application, an eddy correlation apparatus would need to be capable of continuous, unattended use at remote sites.

The equipment previously used at Thetford was modified and upgraded last year by merging with proprietary sonic anemometer hardware, and re-sited at an experimental test site at Stadhampton, a few miles from the Institute. This hardware, shown on the front cover, provides evaporation measurements, using the energy budget/Bowen ratio technique, and turbulence measurements, for comparison with prototype eddy correlation sensors developed at the Institute.

Plant physiological controls of evaporation

Bracken Estimates of total water loss from forested areas ought to include the contribution made by any understorey vegetation present. Transpiration by the bracken at the Thetford site was estimated by calculation of the Penman-Monteith equation incorporating a surface resistance obtained from stomatal resistance (r_s) measurements and leaf area index (*LAI*) made throughout the summer of 1976. Aerodynamic resistance (r_a) was estimated from the water loss of a wetted replica of a bracken plant constructed out of blotting paper mounted on wire frames. It was also necessary to know the surface temperature and leaf area of the replica and the absolute humidity of the ambient air. Values of r_a obtained were similar to those calculated from wind speed and crop height.

Transpiration rates of bracken rose from about 5 per cent of the forest total in June (at this time the bracken canopy was still developing) to as much as 50 per cent in July falling to around 30 per cent in August and 20 per cent in September and October. The high contribution of the bracken to total forest evaporation in July is probably due to a more severe limitation of transpiration by the trees having high surface resistances coincident with high atmospheric humidity deficits. The lower contribution to the forest evaporation by bracken after July is probably more typical of results to be expected in years of less extreme climatic conditions than those experienced in 1976.

Scots pine and Corsican pine Previous work on the physiological controls of evaporation have been limited to Scots pine at the Thetford site but as future Forestry

Commission planting policy in the south and east of England will favour replacing this species with the botanically similar Corsican pine, water use studies on separate stands of the two species have been carried out using several different techniques. These were:

(1) Calculation of the Penman-Monteith evaporation formula using surface resistance values calculated from *LAI* and r_s data in the two stands.

(2) Direct comparisons of water uptake using the tree cutting technique (Roberts, 1977).

(3) Comparison of sensible heat fluxes above the two stands using eddy correlation equipment.

(4) A comparison of soil water use as measured by a neutron probe.

(5) Throughfall measurements were also made in both stands.

Analysis is still in progress but it seems that individual leaf stomatal resistances of the two species are similar and if *LAI* of the trees in each stand are also similar, transpiration is likely to be the same. Corsican pine may develop a greater *LAI* than Scots pine on some sites, however, and as a tree component of any forest system can then presumably transpire more. Conversely, the forest floor of a Scots pine stand would be better illuminated and would support an understorey (of bracken, for example) which would probably have a not insignificant water use itself and could make up any differences in the water loss of the two tree species.

Interception

Many conclusions drawn from hydrological research are qualified with the restriction that the results apply only in the place where the observations were made and therefore cannot necessarily be extrapolated to other areas. This is particularly true of the evaporation of rainfall intercepted by forest canopies, which depends on such variables as radiation, rainfall and the structure of the forest. More generally applicable results are therefore required and individual aspects of the forest water balance have been studied in detail to produce a better understanding of the fundamental physical principles controlling the interception process.

An estimate of the evaporation from Thetford Forest during 1975 (Gash and Stewart, 1977) showed that for Thetford, which is in the low rainfall area of East Anglia, there was likely to be little appreciable difference between the evaporation from forest and grass. Such a conclusion might appear contradictory, if compared with the results from Plynlimon, were it not explained in terms of lower rainfall resulting in a shorter duration of canopy wetness and therefore in a lower interception loss. Rainfall and rainfall duration vary greatly over the British Isles and any attempt to predict the effect of a change in land use from forest to grass, or to estimate the water loss from an existing forest, must take into account the consequent variation in the interception loss.

There are several methods available for estimating the evaporation of rainfall intercepted by forests: the numerical model developed by Professor Rutter and his group at Imperial College is probably the most rigorous and, in co-operation with Imperial College, this model has been tested against the Thetford interception measurements, with satisfactory agreement (Gash and Morton, 1978). The model is currently being tested against similar data from Plynlimon. As an alternative, an analytical model of interception loss (Gash, 1979), has been developed which, despite several simplifying assumptions, retains much of the physical reasoning of the more complex Rutter model. The model calculates interception loss on a storm by storm basis, separating the fraction of evaporation which occurs during the rain storm from that which occurs after the storm. In this way the meteorological and biological controls are separately identified to give a framework within which results may more readily be extrapolated to other areas.

Forest interception loss and the meteorological variables controlling evaporation are currently being measured in the Kielder Forest in Northumberland and in the Savernake Forest in Wiltshire. These will be used to test the models further and to provide additional knowledge on the areal variation of evaporation between regions of differing climate.

Process studies are in hand at Plynlimon to understand the mechanisms of evaporative loss from forest and grassland in this high rainfall environment. The experimental techniques have involved the use of (a) a 'natural' forest lysimeter, (b) the lysimeter covered with plastic sheeting to exclude rainfall, (c) large plastic-sheet net-rainfall gauges, (d) diffusion porometry, (e) tree cutting experiments, (f) leaf water potential pressure bombs and (g) fibreglass tank monolith lysimeters.

Measurements from these different experimental techniques have been used both to develop a model of transpiration and interception loss from spruce forest based on the Penman-Monteith equation and to derive the model parameters by optimisation. The surface resistance parameter was found to be well fitted by the semi-empirical equation:

$$r_s = 74{\cdot}5\left[1 - 0{\cdot}3\ \cos\ \left\{2\pi\left(\frac{D-222}{365}\right)\right\}\right] / (1 - 0{\cdot}45\ \delta e)$$

r_s infinite for $\delta e > 2{\cdot}2$

where D is the day number of the year and δe is the vapour pressure deficit in kPa. The aerodynamic resistance was found to be 3·5 sm^{-1}. Further experiments have since confirmed certain of the model parameters (Roberts 1978, Calder 1978a) so that comparisons of model predictions with observations could be made over an extended time period, as shown in Figure 18.

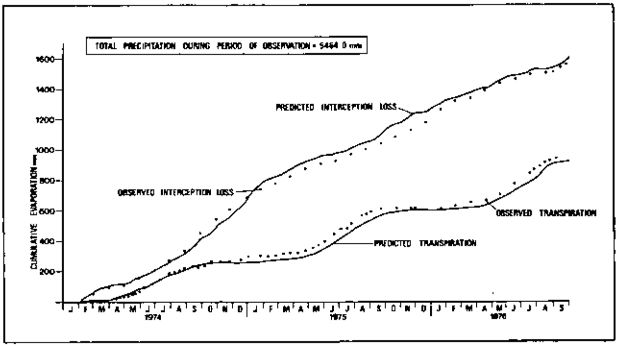


Figure 18. *Observed and predicted evaporation loss from the forest lysimeter*

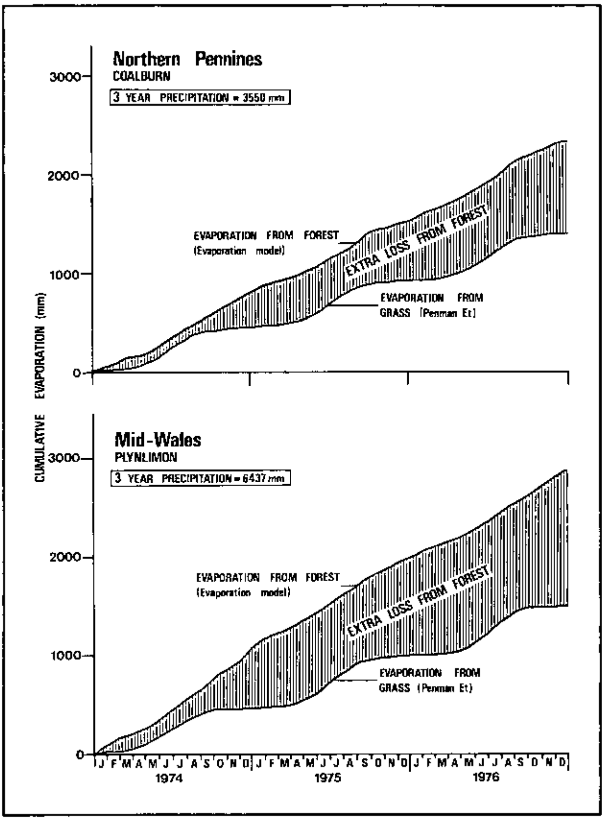


Figure 19. *Predicted cumulative evaporation loss from spruce forest (with complete canopy closure) and grass in the northern Pennines and upland mid-Wales for 1974, 1975 and 1976*

Figure 19 predicts the extra losses from spruce forest with complete canopy closure as compared with grass under the different climatic conditions appropriate to two of the hydrologically important upland areas, Mid-Wales and the Northern Pennines, for the years 1974, 1975 and 1976.

Current development of the models is towards estimating the effects upon water yields of afforestation in upland areas. This work involves the development of a climatological data base, an investigation of model accuracy and parameter sensitivity, an experimental study of the evaporation characteristics of other upland crop types, an investigation into the evaporation/atmosphere interaction and the final production and verification of the generalised computer-based model ready for its eventual application by the water industry.

Evapotranspiration depends strongly on the surface heat budget, the net gain of energy at the evaporating surface, which is of course dominated by solar radiation. One of the terms of this energy budget, the flux of heat into and out of the ground, has often been neglected on the assumption that heat flow is cyclic, most of the heat absorbed during the day being returned at night. However, a seasonal imbalance does exist, and an effort is being made to compute daily net heat fluxes for the Plynlimon catchments, using simple soil temperature and meteorological measurements.

In the literature of soil heat, much use has been made of known solutions of the diffusion equation with periodic boundary conditions. A better approach for British conditions is digital simulation of measured non-periodic fluctuations. A profile model has been developed to simulate the response of soil temperature to measured air temperature and net radiation fluctuations. When combined with laboratory measurements of soil heat capacity the application of this model will give a calorimetric estimate of the daily movement of heat in the soil.

Field measurements of soil temperature are continuing at the Institute's automatic weather station sites in Plynlimon, and recording of air temperature in the trunk space of the forest has been initiated. Early trials of the profile model show a good agreement with observed soil temperatures. (Figure 20).

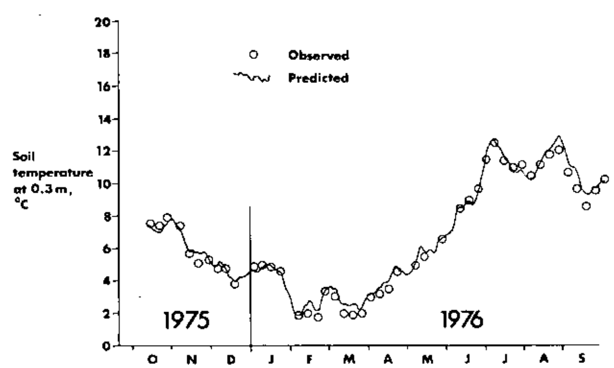


Figure 20. *Simulation of soil temperature from climatological data. Comparison of observed and predicted soil temperature variation over a one-year period.*

Storm runoff through natural pipes

Mapping and flow measurement studies conducted over the last few years have established that an important storm runoff process in the Wye catchment, Plynlimon (and probably in other grassed upland areas) is the rapid transmission of water down-slope through cavities in the soil. The importance of the markedly inhomogeneous and anisotropic behaviour of Plynlimon slope soils has been realized for some time. A wide variety of crack, fissure and pipe flows has been observed, the most spectacular being the flow during heavy rainfalls from soil pipes at the base of the 'A' horizon in the peaty podzolic soils of the Wye catchment.

Research on these intermittently-flowing pipes has followed two main directions:

(a) Mapping and survey techniques, both on a catchment scale to define the association of pipes with particular conditions of soil, slope and runoff and also detailed plot-scale surveys of pipes to define their network properties, geometry and location in the soil profile. This has been backed up with bulk soil physical tests to suggest pedological constraints on the origin of pipes.

(b) The measurement of pipe-flow, storage capacities, mean velocities of flow, and sediment load, to be incorporated into an element representing pipe flow for use in distributed catchment models.

Pipe origin Burrowing mammals play a role in pipe formation but this is very much subordinate to dessication cracking (shown especially by excavation during the 1975–76 drought, see Figure 21), followed by fluvial erosion of the oxidized peat from the crack walls. Yields of peat and mineral 'bedload' are considerable even from established pipes. The dessication/erosion hypothesis is supported by the fact that pipes occur mainly in the peaty podzol soils of the catchment in well-drained sites (becoming increasingly well-drained

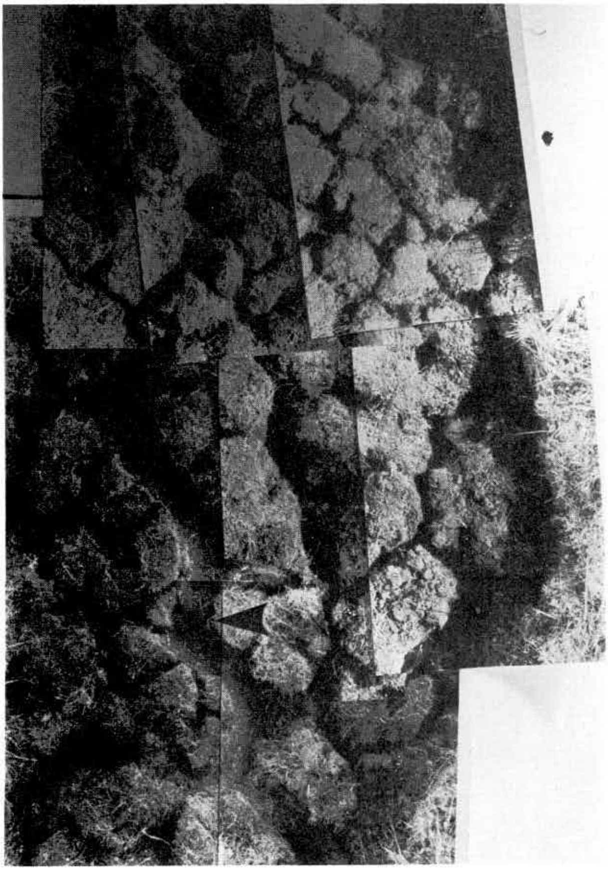


Figure 21. *Composite photograph of cracking in peaty 'A' horizon, Wye catchment. Pipe runs down left hand side of picture*

as pipes develop) and mainly at the A/B horizon junction in the soil profile.

Hydrologically, the pipes are important over their own catchment area, transmitting flows at velocities of ·07 to ·20 m/s over discharge ranges for which overland flow velocities are ·001 to ·008 m/s. However, they fill up during flood conditions and the resulting overflow produces the characteristic 'pipe springs'. The complex inter-relationship with runoff from the blanket peat above and the overland flow system (with which pipes share in the transfer of slope runoff to channels) results in a less flashy regime for a piped slope than would be hypothesized from a comparison with surface channel flow.

The simulation of surface runoff has received much attention in the literature and distributed modelling of pipe flow incurs similar problems. A process with inherent spatial variability must necessarily be simulated as a process distributed uniformly (or at best smoothly) over each cell of the model. Mapping techniques are not sufficiently precise to allow the incorporation of elements representing individual pipes, and the simplest approach is to use a state-discharge model, with the state variable computed as the total water content of the surface zone (flowing water and depression storage) and the shallow sub-surface zone. It is hoped to use a model incorporating a matrix flow, formulated as saturated groundwater flow on an inclined bed, and a pipe flow whose direction is orthogonal to the ground surface contours and whose discharge, per unit length of contour, is a prescribed function of the state variable. The nonlinear partial differential equation to be solved is:

$$\nabla((Kz\nabla h + f(z-z_o) \frac{\nabla h}{s^{1/2}} H(z-z_o)) + P = S\frac{\partial z}{\partial t}$$

where

z is the state variable, taking the value z_0 at field capacity when drainage through pipes ceases

h is the height of the ground surface above datum

s is the ground surface slope

f is a given monotonically increasing function of $z-z_0$

P is the precipitation rate, allowing for interception by the short vegetation cover

H $(z-z_0)$ is the Heaviside unit function (1 when $z > z_0$ and O otherwise) and K and S are constants. Preliminary experiments have shown that this equation can be solved by a suitable modification of the alternating-direction implicit procedure of Peaceman and Rachford.

Contributing area and channel studies

Channel cross-sectional data from the Plynlimon catchments have been collected and travel times calculated using fluorescent dyes. The relationship between channel-full cross-sectional area and catchment area is as follows:

$$C = 1 \cdot 66A^{0 \cdot 52} \qquad (r^2 = 0 \cdot 545)$$

where C is channel capacity and A is catchment area.

Individual dimensions of the cross-section vary in their response to increasing catchment area as follows:

$$W = 2 \cdot 40A^{0 \cdot 42} \qquad (r^2 = 0 \cdot 635)$$
$$D = 1 \cdot 87A^{0 \cdot 07} \qquad (r^2 = 0 \cdot 023)$$

where W is channel width and D is channel depth.

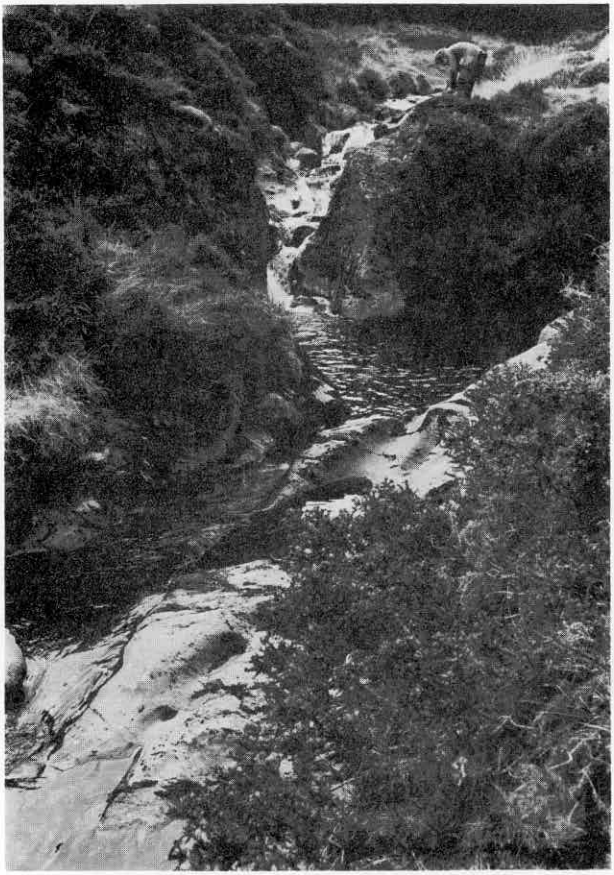


Figure 22. *Bedrock and pool above Blaen Hafren falls, Hafren catchment*

The preferential increase of channel width is one demonstration of the control by rock outcrops on the channel bed. Travel time curves show that the minimum travel time is effective at all discharges above about half mean-annual-flood, suggesting linearity of response in the channel phase of runoff. The curvilinear relationship below this level, however, suggests the need for non-linear approaches to continuous flow modelling.

At the channel reach scale, dilution tests at seven reaches in the Severn catchment have produced data for a storage routing model for rough channels. Here the increase of flow depth with discharge is noticeable, as is that of mean velocity for the reach. At high flows the complex roughness elements of the channel bed and profile are 'drowned' and total storage in the reach approaches 'active' storage.

The viability of a vegetational classification to define runoff contributing areas within catchments has been proved using data from the Wye catchment. This is a technique which shows promise for hydrograph modelling. Accordingly, data from seventeen small catchments, each including continuous rainfall, runoff and soil water-level measurements, are being put through a simple hydrograph analysis. The sample aims to assess the runoff performance in rainstorms of deep peat, well-drained slopes (with soil pipes) and valley-bottom mires as natural source areas, with tile-drained plots and forest ditches as a check on 'artificial' influences.

Artificial drainage

The Institute's involvement with the River Ray catchment (18·5 km^2) at Grendon Underwood goes back to 1962. Since then, there has been an increasing area within the catchment that has been drained by mole and tile drainage. The effects of this type of drainage on the hydrological response of the complete catchment is now being investigated.

Firstly, there is the need to understand the response of both drained and undrained areas in the catchment and, two plots of about 1000 m^2 each have therefore been instrumented. The soils of the plots are of the Evesham series developed on a parent material of Oxford clay. The profile below the 15–30 cm rooting depth is predominantly a heavy clay of low permeability. The two plots contribute discharge to an existing ditch and have been isolated on the upslope side by a tile drain. The plots have a very low slope towards the ditch but are situated on an historic 'ridge and furrow' system at right angles to the ditch. The ridge and furrow topography is common on the clay pasture land of the River Ray catchment and predates the enclosure of the present fields in the late 18th century. The mole drains on the drained plot run parallel to the ridge and furrow and contribute to a tile drain across the base of the plot. Outflow from this tile drain is monitored by a V-notch weir box with a 1:1 stage recorder. On the undrained plot, a shallow (20 cm) tile drain backfilled with gravel is used as a surface and near-surface outflow collector, and is connected to a similar V-notch flow measurement system. Tensiometers, neutron probe access tubes and surface flow detectors are used within the plots to assess the response of varying soil moisture conditions.

Preliminary results show that the drains maintain a lower water table on the drained plot eliminating the standing surface water commonly found on the undrained plot. The wet furrows on the undrained plot are seen quite clearly on the right hand side of the red filtered photograph, Figure 23. However, the drained

Figure 23. *Drained and undrained plots at Grendon Underwood*

plot also appears to yield significantly higher storm discharges than the undrained plot with steeper rising and recession limbs to the storm hydrograph.

Surface flows

Water temperature studies

This project is operated under a CASE Award with the Department of Geography, University of Strathclyde. It is intended to relate hourly stream temperatures to meteorological and hydrological variables and to use proven relationships for prediction.

So far, the student has installed thermographs registering 'source' water temperature and 'channel' water temperature in both the Severn and the Wye. Point measurements are made monthly at forty sites, weekly at the eight flumes and there are six monthly-read maximum/minimum stations. Soil temperature variation at 5 cm and 30 cm depths is measured at eight sites and a specially-adapted automatic weather station records channel-level meteorology. To index forest conditions, automatic weather station data (canopy level) from the natural lysimeter study (see page 45) will be used, with two Stevenson screens amongst the trees in the Severn forest.

As well as defining a prediction relationship for use in assessing the impact of land-use change on stream ecology, the study is expected to yield useful methods of 'tagging' water from various runoff zones to improve hydrological modelling.

Flow and flow routing in steep, rough upland channels

In the upland headwaters of catchments, from which a significant proportion of flood runoff may be derived, river channels are small, steep and rough. The problem of defining flow relationships in such channels has been neglected in past studies of open channel flow. Flow along a channel reach may involve slow pool segments, fast upper and rapid segments, waterfalls and other irregularities in the channel bed, creating rapid changes in flow depth, width, and channel roughness. In addition, the nature of flow may change with increasing discharge, as individual roughness elements and channel irregularities are drowned out. There is therefore a need to improve upon the use of uniform flow relationships for routing models in this type of channel, where in general the flow is non-uniform and apparent roughness coefficients for complete channel reaches are unreasonably high.

For flow routing purposes complex interactions between tumbling, tranquil and rapid flow need to be integrated. The gulp dilution gauging method provides a convenient tool to investigate the nature of flow over complete reaches and is used to obtain estimates of discharge, average velocity and residence time distribution of the active storage in the reach. Relationships between discharge and velocity may be determined by taking measurements at a number of flow stages. Such measurements have been made for a

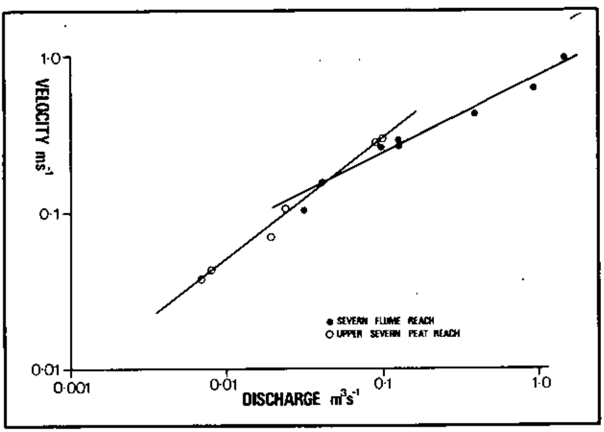


Figure 24. *Average flow velocity/discharge relationship for upper Severn and Severn flume reaches*

number of reaches in the River Severn catchment at Plynlimon. Flow at low stages is markedly non-linear both at a station and in the downstream direction (see Figures 24 and 25). At higher flow stages, of the order of the mean annual flood flow, velocities over the network as a whole tend towards a constant value (Figure 26). The results suggest that channel routing may be

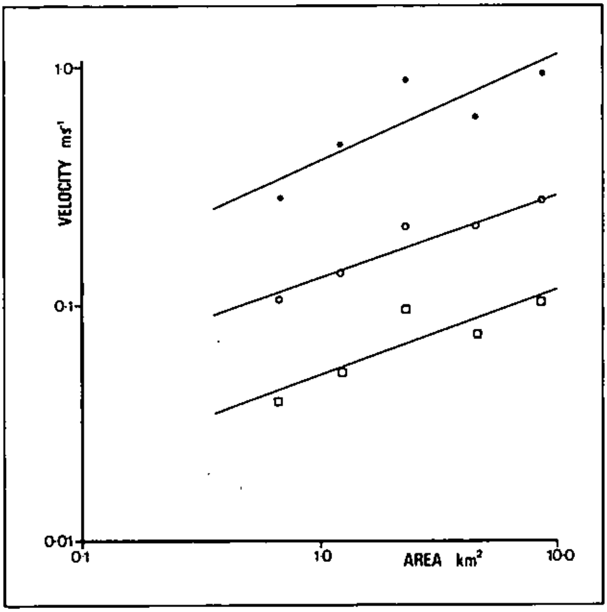


Figure 25. *Average flow velocity/catchment area relationships for River Severn measurement reaches at three flow stages*

an important modifying influence on the form of the flow hydrograph even in small upland channels. For routing flood flows a simple linear convolution procedure based on a constant kinematic flow velocity and the channel length frequency distribution of the network may be sufficiently accurate. For routing lower flows however, non-linear kinematic routing procedure must be used. In either case, the dilution gauging method provides an effective and, when compared with the cost of detailed survey techniques, an economic means of obtaining the routing parameters by measurement in the field.

Chemical dilution gauging

Although dilution gauging is simple in principle, obtaining reliable results in the field requires a precise, methodical technique and a detailed understanding of the processes of mixing and transport of tracers in streams. Too often in the past dilution methods have been presented as quick, inexpensive and easy of application, and this approach has led to dis-

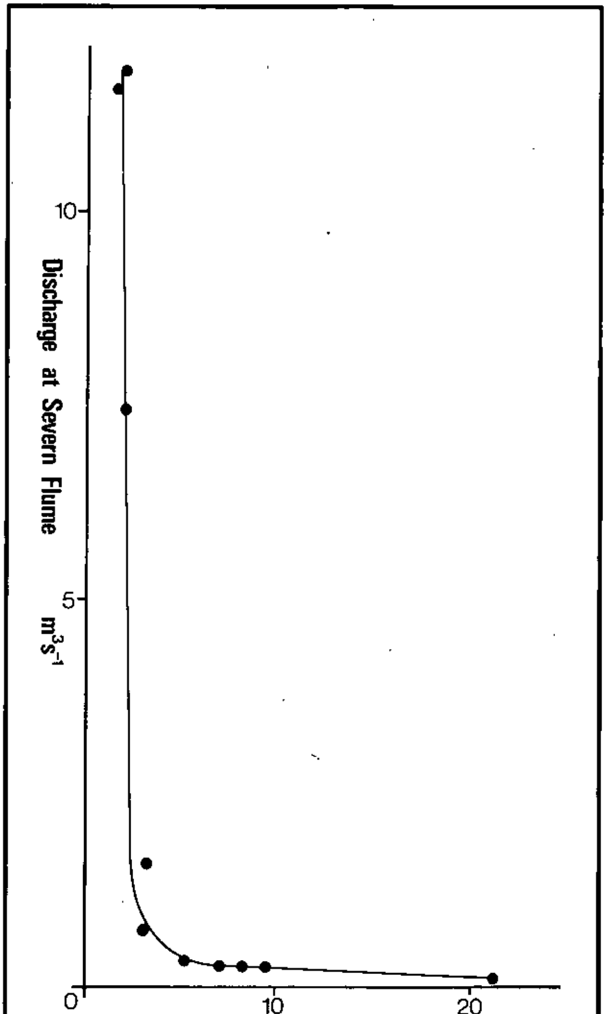


Figure 26. *Results of tracer travel time measurements at different discharges over the mainstream River Severn*

appointment and erroneous results. By refining field and laboratory techniques and by theoretical analysis the Institute aims to establish the dilution method as a precise point-gauging method with a special field of application, as for example in turbulent non-uniform flow, where it is second to none.

Dilution gauging, like the velocity-area method, is usually considered as a means of measuring *steady* flow.

Extension of the theory to unsteady flow has continued with a consideration of smoothly varying discharge, such as may be encountered on the recession limb of a hydrograph (Gilman, 1977a, 1977b). A systematic error is caused by changes in storage in the gauging reach as the discharge varies. A model of tracer movement in the reach has confirmed that this error is similar in magnitude to the alteration of discharge during the gauging. For a detailed explanation, formulae and worked examples, the reader is referred to the above papers.

Tests of dilution gauging in the field against other methods have been few, mainly for economic and logistic reasons, but also because gauging structures generally cause a reduction in the mixing ability of the stream, while streams suitable for the velocity-area method require long mixing distances. The steep mountain streams for which dilution methods are most appropriate are not usually instrumented, but the Institute is unique in Britain in having hydrometric structures on several such streams.

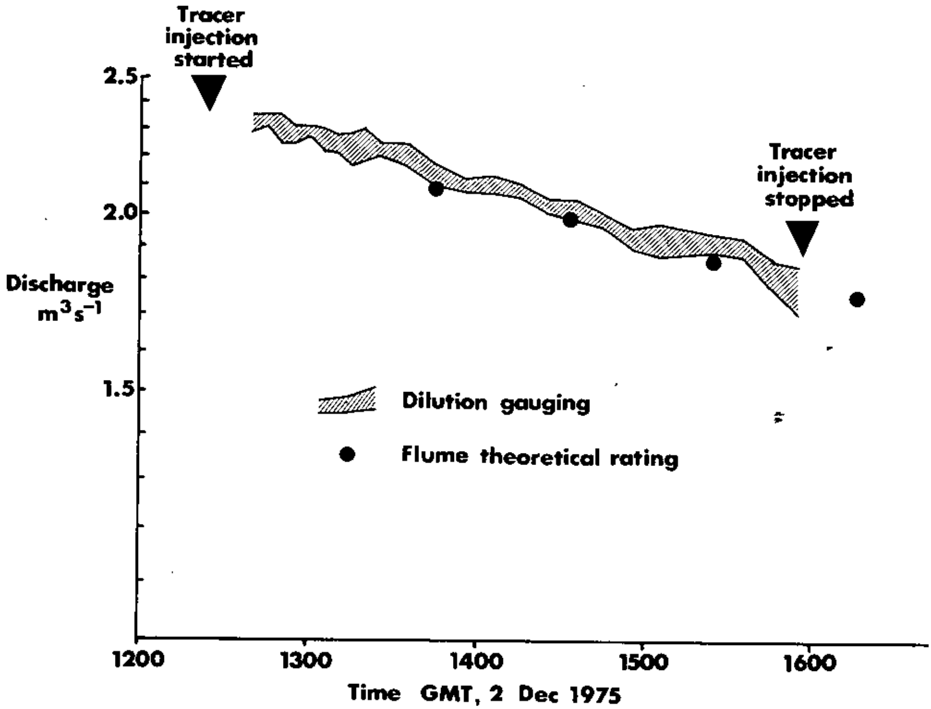
Difficulties were encountered initially with the long passage time of tracer in the gauging reach. Using the constant injection method, steady 'plateau' conditions were obtained only after 15 times the time of arrival of the tracer, a result which demonstrated the effectiveness of pools in delaying the passage of tracer.

Much of the dilution gauging work at Plynlimon was carried out as a calibration of the structures for stages below the threshold of the theoretical ratings (Smart 1977). This, in addition to the problems of failure to achieve plateau conditions, meant that only a few measurements qualified as comparisons between gauging methods.

Flow through the Severn trapezoidal flume was gauged on the falling limb of a storm hydrograph using a $3\frac{1}{2}$ hour constant rate injection of sodium iodide. The agreement between the dilution gauging estimate and the structure's theoretical rating was within two percent (Figure 27).

During the drought of 1976 it proved possible to channel the outflow from each of the six minor structures into tanks for precise volumetric gauging (Smart, 1977). Simultaneously, the flows were gauged using a

Figure 27. *Gauging of the River Severn by tracer dilution. Comparison of theoretical rating with dilution gauging results*



constant rate injection of sodium iodide. The results, summarised in Table 3, show small discrepancies which are thought to be due to leakage from the stream reach in the drought conditions, while the large error in the Nant Iago gauging was caused by percolation with a travel time of many hours through a midstream gravel bar.

Table 3. *Low flow comparisons between volumetric and dilution gaugings of steep stream structures in Plynlimon. Units:* $l\ s^{-1}$

	Stream	Volumetric gauging	Dilution gauging
SEVERN CATCHMENT	Afon Hafren	14·25 ± 0·14*	14·50 ± 0·25
	Nant Tanllwyth	1·85 ± 0·01	1·98 ± 0·04
	Afon Hore	9·73 ± 0·08	10·12 ± 0·17
WYE CATCHMENT	Nant Iago	2·46 ± 0·01	5·81 ± 0·07
	Afon Gwy	15·65 ± 0·12	15·96 ± 0·20
	Afon Cyff	6·96 ± 0·07	7·41 ± 0·09

* Tolerances quoted are 95% confidence limits.

Unsaturated soil water flow

Water and nitrate fluxes in unsaturated chalk

In 1972 an experiment was set up by the Agricultural Development and Advisory Service and the Ministry of Agriculture at Bridgets Experimental Husbandry Farm, near Winchester, to investigate the effect of inorganic fertilizer and animal waste slurry applications to grassland on the nitrate nitrogen content of the interstitial water in the unsaturated zone of the chalk. The Institute was invited in 1976 to participate in the experiment, particularly to investigate the water fluxes in the chalk needed to quantify nitrate flux. The experiment is relevant to two areas of concern—the possible long-term pollution of the chalk aquifer by nitrate of agricultural origin and the efficiency of applied nitrogen fertilizers. A further application is in clarifying the mechanisms of water and solute movement in unsaturated chalk.

Water fluxes are calculated using simultaneous measurements of water content and tension to 3 m depth in the chalk throughout the year. During the winter, drainage is estimated from a water balance:

$$D = R - E - \Delta S$$

where D = drainage, R = rainfall, E = evaporation (Penman E_t), and ΔS = change in soil water storage. Runoff is assumed to be negligible. During the summer, the zero flux plane (ZFP) method is used to partition water fluxes into evaporation (upwards) and drainage (downwards). This depends on using tensiometers to identify the depth at which the potential gradient—and hence the flux—is zero. Once this is established, the fluxes can be quantified from water content measurements.

Water content throughout the profile is measured by neutron probe, while water tensions are measured by mercury manometer tensiometers, calibrated gypsum resistance blocks and pressure transducer tensiometers. Interstitial water is sampled by *in situ* ceramic cup suction samplers and the water is analysed for nitrate nitrogen by ADAS. The experimental plots receive four treatments; control (no added nitrogen), inorganic fertilizer at 376 kg/ha N as ammonium nitrate, ten winter applications of cow slurry equivalent to 10 cows/ha, and likewise at 40 cows/ha. The Institute instrumented the control and the 40 cows/ha slurry plots in May–July 1976, together with pressure transducer tensiometers installed to 9 m in a borehole adjacent to the site. The soil of the experimental site is Andover series with approximately 0·3 m of a silty loam 'A' horizon overlying the chalk which is in a comparatively fresh and seemingly undisturbed condition.

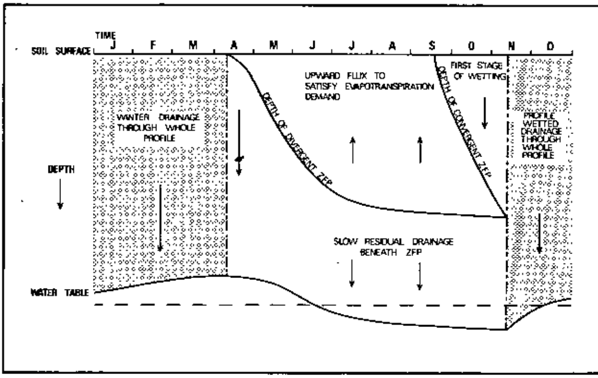


Figure 28. *Seasonal partition of water fluxes by the Zero Flux Plane in the unsaturated zone of the chalk*

Figure 28 illustrates diagrammatically the seasonal changes in the unsaturated fluxes and their upward and downward partition by the zero flux plane. A selection of potential profiles is given in Figures 29 and 30 illustrating the drying and re-wetting sequences and the movement of the zero flux planes during 1977.

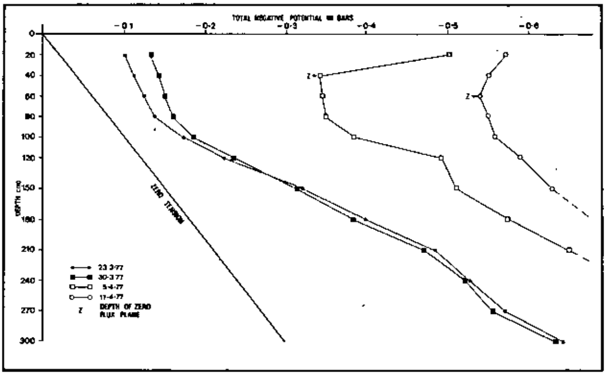


Figure 29. *Total potential profiles derived from mercury manometer tensiometers: Plot 1, Control, Bridgets EHF 1977*

Figure 29 shows potential profiles derived with mercury manometer tensiometers, initially with steep downward gradients (of approximately twice gravity) and the first appearance of a stable zero flux plane on the 5th April; tensions then increased throughout and the last profile within manometer tensiometer range was on the 11th April. Thus it is seen that rapid drainage through the entire profile from the surface ceased at the beginning of April. For the remainder of the summer, data for the upper profile were obtained from the gypsum blocks. These indicated a rapid plunge of the zero flux plane in early July reaching the dryest profile on 10th August (Figure 30), with the zero flux plane at about 6·5 m. At this stage flow was transmitted upwards through the entire upper 6·5 m of the profile to supply the evapotranspiration losses. Decrease of evapotranspirational demands coupled with increased rainfall caused the initiation of a rewetting front, represented by the convergent zero flux plane shown for 12th October. This moved rapidly down the profile until the two zero flux planes met at 6·5 m at which time a downward gradient was reinstated throughout the profile and the winter recharge stage commenced (profile of 1st February).

These results suggest that nitrate in solution would have been moving upwards to the root zone of the plants for a substantial period during the summer and from substantial depths. The implications of this upward flux of nitrate are not yet clear but it may have considerable importance in developing an understanding of the process of nitrate transport through the unsaturated zone of the chalk.

Very few samples of interstitial water have been obtained from the suction samplers since they were installed in September 1972. It is now clear that the principal reason for this is the low matric potentials ($< -1 \cdot 0$ bars or 0·1 MPa) which occur in the chalk for nine months or more of the year, during which period the suction sampling method could not work.

Data for the 12-month period September 1976–October 1977 have been analysed, and evaporation and drainage have been partitioned for the period. On the control and 40 cows/ha plots evaporation was 398 mm and 409 mm respectively.

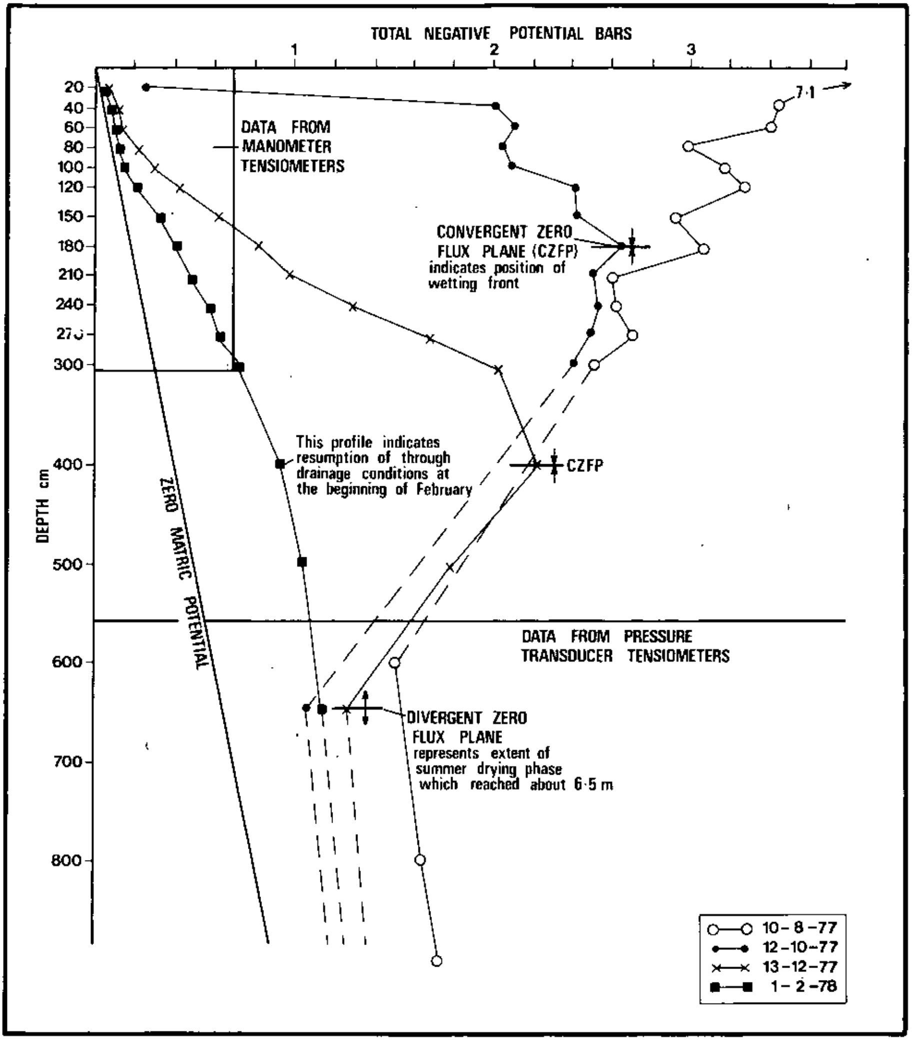


Figure 30. *Total potential profiles from gypsum blocks, pressure transducer and mercury manometer tensiometers, Bridgets EHF 1977–78*

Drainage for the winter period, October 1976–April 1977 was 396 mm and 518 mm respectively. Drainage at 3 m following the onset of ZFP conditions at the surface became negligible. The higher drainage on the 40 cows/ha plot is accounted for partly by the water applied in the slurry (70 mm), and partly by the observed suppression for 2 weeks or more of early grass growth due to the slurry residue. Very few interstitial water samples were obtained during the 1976-7 winter, and hence calculations of nitrate fluxes were not justified.

To obtain interstitial water samples regularly and reliably, a sequential core sampling programme has now been started together with the continuing water flux measurements. Nitrate analysis of centrifugued extracts will be used to follow the seasonal movements of nitrate in the upper part of the chalk throughout the year.

There are two possible mechanisms for water movement in unsaturated chalk; flow through microfissures and flow through the matrix. It is hoped that the measurements will show the extent to which each of these processes is important for aquifer recharge in chalk, and the physical conditions which control them. This is important for understanding and predicting the long-term pollution of chalk aquifers by nitrate.

Groundwater recharge, soil physical methods

Water resource engineers usually estimate aquifer recharge from the difference between rainfall and an estimate of evaporation based on Penman's equation. In East Anglia the likely error in the determination of both these parameters is of the same order of magnitude as the difference between them, so that aquifer recharge estimates may contain large errors. A joint three-year project with the Institute of Geological Sciences was started in April 1977 on the site of the Fleam Dyke Pumping Station, just outside Cambridge, and is being funded by the Department of the Environment. The Institute is using soil physical methods to measure downward fluxes directly which should lead to a more accurate method of estimating recharge, and one which can be used on a routine basis by the water industry. Results will be compared with those derived from the nearby undisturbed five metre cube drainage lysimeter operated by the Institute of Geological Sciences and also with the standard meteorological methods.

Instrumentation Two plots are instrumented as shown in Figures 31 and 32. On each site there are four access tubes, three of which are 3·3 m deep while a fourth is 12·0 m deep, to allow measurements of the soil moisture content profile of the chalk below the plots using a

Figure 31. *Plan of the Fleam Dyke experimental site*

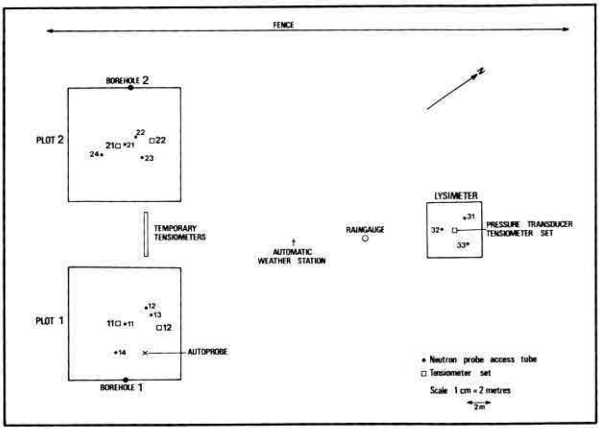
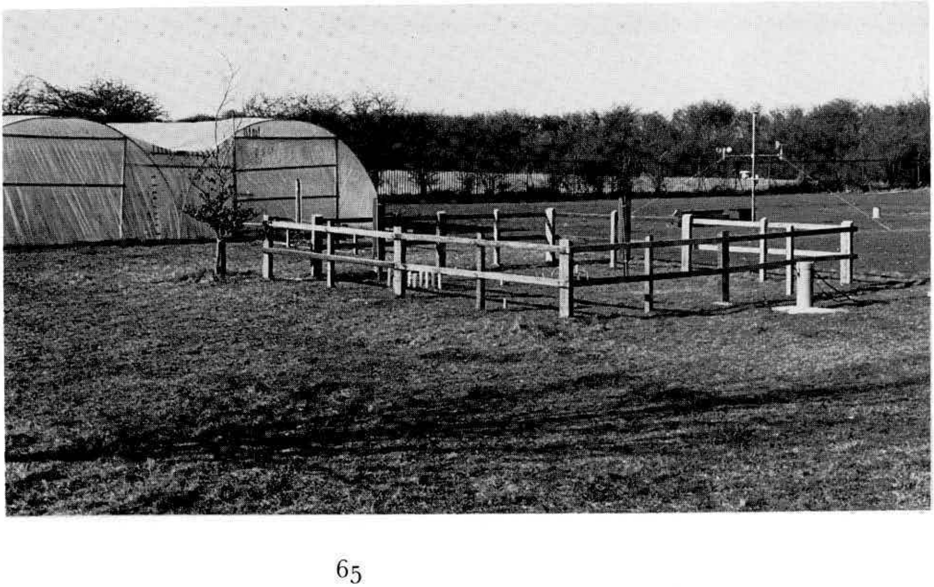


Figure 32. *The experimental site at Fleam Dyke with the automatic weather station in the background. The far plot is covered with a polythene greenhouse in which an experiment to measure the unsaturated hydraulic conductivity of the chalk is taking place.*

neutron probe. In addition, plot 1 has an automatic neutron probe (or 'Autoprobe'). Two sets of mercury manometer tensiometers are also operating on each site to provide soil moisture potential profiles to a depth of 3·0 m. Finally, on the edge of each plot there is a 35 m deep, 150 mm diameter borehole (intersecting the water table at a depth of 20 m) into which are inserted pressure transducer tensiometers recording in digital form on tape cassettes. An automatic weather station and raingauge are situated nearby for comparison of results with recharge calculated from



meteorological information. The IGS lysimeter has three 5 m deep neutron probe access tubes and a set of five purgeable pressure transducer tensiometers at depths between 1 m and 4·5 m. The data from these latter instruments will be used to compare the processes within the lysimeter with those in the natural profile outside.

Measurement interpretation Daily readings of soil moisture content and tension have been made on both plots since July 1977. Since March 1978 readings of soil moisture tension in the two boreholes and in the lysimeter have been made every 15 minutes by means of the pressure transducer tensiometers.

Soil moisture fluxes, both upward and downward are then determined by the zero flux plane method (Bell, 1976), when a zero flux plane exists, or at other times from the application of Darcy's Law

$$v = -K\frac{d\phi}{dz}$$

where v is the soil moisture flux, K the unsaturated hydraulic conductivity, ϕ is the soil moisture potential and z the depth below the soil surface. For this latter method the unsaturated hydraulic conductivity characteristics beneath each plot must be measured. An experiment to determine these, i.e. the curves relating conductivity to water content, is now in progress on plot 2, see Figure 33.

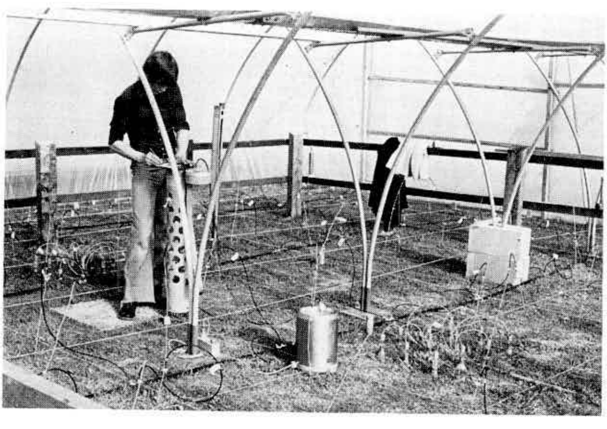


Figure 33. *The unsaturated hydraulic conductivity experiment in progress under the greenhouse. Note the network of drippers supplying water to the surface at a controlled rate, one of which is monitored continuously by the tipping bucket raingauge attached to the solid-state memory shown in the foreground. Also shown are three of the four access tubes, one of which is being read by a neutron probe and the others by two sets of twelve mercury manometer tensiometers*

Three additional sites within a couple of miles of Fleam Dyke are being instrumented to investigate the areal variability of recharge. All these sites are on permanent grassland for ease of instrumentation but the method could be adapted for other crops.

Saturated soil water flow

Thatcham reedbeds hydrological survey

At Thatcham, in the Kennet valley, there is an area of fenland which supports a growth of reed and associated flora and fauna; this is classified as a Site of Special Scientific Interest by the Nature Conservancy Council. A hydrological survey conducted by the Institute for Newbury District Council has demonstrated that concern over the effects of imminent gravel extraction from part of the site was justified.

Periodic observations of groundwater levels at ten sites between August 1975 and May 1977 showed that natural fluctuations in the water table should not exceed 0·6 metres, and most sites had a range of about 0·3 metres, even in the 1976 drought. However, when dewatering for gravel extraction began in October 1976 a cone of depression was quickly established, and water levels fell below the base of the peat. There was no recovery of groundwater levels during the winter of 1976–7.

The final report on the Thatcham study was prepared at a time when groundwater levels were falling rapidly but no effect on the plant community was yet apparent (Gilman, 1977d). Measurements of the reeds in the late summer and autumn of 1977 have shown that the height and girth of reeds near the excavations are less than in the previous year, when compared with controls growing in shallow water (Table 4). In some areas the reeds did not flower in 1977, and nitrate released from the dewatered peat has encouraged nettles to invade the largest reedbed. By comparison, reeds growing near to a flowing ditch excavated in February 1976 have increased in stature and mosses have begun to colonise the ground between the stems. It is therefore likely that the reedbeds could still be

Site	1976 reeds standing on 4.8.77	1977	
		4.8.77	28.10.77
Kennet & Avon Canal (Controls growing in water)	2·72 (mean of 24)	Immature	2·71 (mean of 20)
Borehole 19 (500 m from excavation)	2·34 (mean of 7)	Immature	1·95 (mean of 19)
Borehole 10 (150 m from excavation)	2·08 (mean of 14)	1·85 (mean of 11)	Damaged by wind
Local nature reserve. (Irrigated by new ditch)	1·73 (mean of 14)	1·98 (mean of 12)	1·92 (mean of 16)

Table 4. *Measurements of the height (in metres) of flowering reeds at Thatcham.*

rescued by the irrigation works which are recommended in the Thatcham report.

Taking the reeds in the canal as a control, comparisons with the three other sites for 1976 and 1977 (where possible) yield significant differences. Only the canal site shows no significant change from 1976 to 1977; all other sites show changes significant at the 99% level.

These deleterious effects of interference with the water regime serve to demonstrate the vulnerability of many of our wetland areas, and the necessity for a detailed hydrological basis for conservation and management.

Hydrogeology

Origin of alkaline groundwaters, Oman

During the survey of the water resources of Northern Oman (1973–75) a number of unusual springs was found in the foothill areas of the Jabal Akdhar. At these sites groundwater emerges as a solution of calcium hydroxide making these springs of up to pH 12·06 some of the most alkaline natural waters anywhere in the world. Calcium hydroxide springs have been attributed to present day serpentinisation. However, they are relatively rare so that the numerous examples and the near-perfect geological exposure in Oman provides an ideal setting for a detailed study of the origin of these remarkable waters and of the chemical and minerological changes associated with them.

The Oman ophiolitic igneous complex comprises rocks originally forming part of the oceanic crust now thrust on to the edge of the Arabian shield. The studies have shown that the springs occur with remarkable regularity at structurally controlled sites at about the horizon of the original Mohorovičić discontinuity. Currently, 38 spring sites have been mapped and samples of water and rock taken for detailed laboratory studies of the chemistry, mineralogy and petrology.

Computer techniques in groundwater resource studies

The objective of this study, funded by the Ministry of Overseas Development, is to produce an integrated system of computer techniques to store, analyse and model hydrogeological data for different resource studies. Based on the methods developed for the recent water resource survey of Northern Oman, the project has been designed to give a rational approach to quantifying groundwater resources with particular emphasis on consistency and presentation of data at the reporting stage. To this end the project has been divided into four parts (i) a data storage and retrieval system; (ii) a set of standard techniques to analyse water level, water quality, pumping test, lithological and well description data, (iii) a set of methods to present data as appendices to a report and (iv) digital modelling studies with particular reference to resource appraisal with scanty data. In the first year of this three year project the work has been concerned with completing the data system and several analytical technique programs.

The data system is a combination of files and programs that present the data for subsequent analysis, quality controlled, with a unique format, ordered and, if required, selected either on a regional basis or on characteristics such as aquifer type and source of water. The programs have been written so that selected subsets of data can be quickly retrieved directly without searching through the whole data set. This is achieved by having two index files, the first containing only the key (grid reference) and the location of the further information. The second index file contains detailed information of the locations of the subsets of different types of data for each key. The data are held in binary form on direct access disc files.

The analytical techniques that have been developed for use with the data system are mainly concerned with water level analysis. These include programs for the interpolation of water level records using cubic splines, estimating water levels for input to digital models, regional water level difference summaries and difference maps for any time intervals in the record. The mapping program is more generally applicable since it can be used for any of the regional data stored on the data system and also is capable of using boundary information stored on a separate file in segments on the data system.

Groundwater model of the Tehran Basin

For several years now the Institute has been studying the groundwater development potential of the Tehran basin in collaboration with Sir Alexander Gibb and Partners. An earlier study, Groundwater and Northern Rivers Tehran Basin Final Report June 1973, completed in 1973, led to the joint development with the Water Research Centre of an electrical analogue model used to test different management schemes for the abstraction of groundwater. Since then, further hydrological information concerning river flow and rainfall has been collected which, together with recent advances in computer-based numerical techniques, has allowed the development of a digital model to simulate the behaviour of the Tehran aquifer.

The differential equation of flow of groundwater in an artesian aquifer is a form of the diffusion equation, with the parameters of storage coefficient and transmissivity distributed in space. The differential equation, with its associated boundary and initial conditions, may be considered as a mathematical model of the system with recharge and water level data considered as input and output respectively.

The finite difference method of successive over-relaxation has been used for the numerical solution of the differential equation and the estimation of the aquifer parameters from historic water level and recharge data developed in the form of an algorithm. The estimated parameters can then be used in the groundwater model. The method splits the estimation into two parts. Firstly, the transmissivities are estimated for periods of balanced recharge using the steady flow equations then, using these transmissivities, the storage coefficient can be estimated using the time-varying flow equations. For both parts of the algorithm a hybrid non-linear optimization method is used to reduce the difference between observed water levels and those predicted from the flow equations.

This new model has been implemented on a computer at the Tehran Water Board so that it can be used *in situ* in conjunction with the analogue model to predict the water level response to various management strategies.

Hydrochemistry

The Institute's hydrochemical work is concerned with the mobility of chemical elements in our natural environment. The problems of element speciation and water/sediment reactions are of particular interest here because these factors complicate the otherwise simple picture of elements being dissolved and transported conservatively by water.

The work with the element iodine has broadened from its original dilution gauging aspect into a study of the movement of iodine species in natural systems. *Ad hoc* studies have already allowed advantage to be taken of the fact that the analytical techniques for total iodine used in dilution gauging can also be applied to marine waters. Accordingly, in collaboration with staff at the Universities of Leeds and Edinburgh both sea waters and sediment pore-waters have been analysed for total iodine. A method has recently been developed for the determination of dissolved iodate in natural waters; however, more analytical work is required before speciation studies in fresh waters are undertaken.

Silicate speciation is also being studied. Here, the approach is to study the different reactivities of silicate species, present in natural waters, to an acidic molybdate reagent, resulting in the formation of molybdosilicic acid. Progress in the development of this aspect of the studies has suffered because of a previous lack of understanding of the chemistry of the silicate/molybdate reaction. Following the studies of the last two years, the reaction can now be defined more fully. In particular, it has been necessary to understand the kinetics of the reaction over a wide range of molybdate and hydrogen ion concentrations. Moreover, because there are two forms of molybdosilicic acid, one of which transforms spontaneously into the other, it has been necessary to make a thorough study of the transformation reaction so that uncertainties in the interpretation of the results of the silicate/molybdate reaction are removed.

Figure 34. *Fen soil profile showing concretionary structures (depth = 2 metres)*

The water/sediment studies continue to be concerned mainly with developing a general method for the determination of the major cations adsorbed on sediments. The major problem of suppressing interference from calcium and magnesium carbonates which are present in most natural sediments has been completed. The interference is overcome by using an ethanolic lithium/caesium chloride leach. To test the method, clay minerals were mixed with various known amounts of calcium or magnesium carbonate before analysis. While in one set of tests homoionic forms were used (Na, K, Ca, Mg), in another set a non-homoionic form (smectite equilibrated with sea-water) was used. The method was vindicated when plots of the amount of cation displaced, against the proportion of clay in the mixture, fitted a linear model well. The method has been used in a preliminary survey of the cation exchange properties of a peat from an alkaline fen in which active carbonate precipitation has occurred. An example of the interesting carbonate nodules found in the fen is shown in Figure 34. The results of cation exchange properties are given in Table 5 together with similar ones which relate to an acid peat bog at Plynlimon.

A second aspect of the water/sediment work continues to be the testing of the effectiveness of tracers for dilution gauging. Earlier work suggested that iodide at a concentration of approximately 50 μg/l would be conserved in most river waters. However, in some recent gauging exercises loss of tracer (up to 35%) to the suspended material has been observed, especially where suspended loads have been high eg. in storm sewers. Notwithstanding the effect of sediment load, however, there is a strong indication that the enhanced loss of tracer is due to an unusually high scavenging power for sediments, probably related to their high organic content. The scavenging properties of these sediments should perhaps be compared with the organic sediment (peat) studied in the earlier work, which also demonstrated high scavenging power. These findings emphasize the need for performing the simple bankside tests for loss of tracer in which river waters are spiked with known amounts of tracer at the time of gauging. Moreover, these results reinforce the

Table 5. *The cation exchange capacities of alkaline and acidic peats.*

Depth (cm)	% Exchangeable cations				Sum of the major exchangeable cations (meg kg^{-1})
	Na	K	Mg	Ca	
Thatcham peat (alkaline)					
0–10	0·7	0·7	0·7	97·8	542
10–20	0·8	0·4	0·4	98·5	528
20–30	0·7	0·1	0·1	99·0	535
Plynlimon peat (acid)					
0–10	11·9	11·2	75·5	1·4	143
10–20	16·7	6·1	75·8	1·5	132
20–30	3·4	3·4	85·5	7·7	117

view that there is no room for complacency in attitudes to sorptive problems. Another tracer, lithium, has been introduced as an alternative to iodide in situations where the latter is likely to be adsorbed. Initial results suggest that lithium will cope with high organic sediment loads.

Applied Hydrology

Flow estimation

Predicting the flood response of natural catchments

The flood estimation techniques in the Flood Studies Report published in 1975 are still subject to refinement and improvement as the data archive on which they were based is continually extended. All gauging authorities have been visited to collect post-1969 records (ie. all information collected after that used in the Flood Studies Report analysis) and the opportunity taken to discuss rating curves and to inspect new stations of interest. Processing of streamflow and rainfall data is virtually complete and a further batch of unit hydrographs has been extracted to add to those derived in the course of the original floods survey. Initially, the confidence limits of the various prediction equations used in the Report will be checked using this extended data base. The main aim of the work however is to examine various alternatives to the linear unit hydrograph model used so far and to attempt to improve the existing percentage runoff model.

It was felt that the Flood Studies Report slope index, S1085, which is the main stream slope between points 10 and 85% of the way along the stream, may not be an adequate indicator of catchment slope as a whole and therefore not the best predictor of catchment response. Thus, various indices of average overland slope have been examined to see whether or not the prediction of percentage runoff (PERC) or the time to peak of the unit hydrograph (*Tp*) can be improved by incorporating some index of overland slope. The possibility of portraying overland slope on a national map was considered but it proved to be impossible to include sufficient detail to enable resolution of slopes on small catchments. It was then realised that what was required was a completely objective technique of measuring average overland slope for any catchment. Three such methods were studied, the Nash method of grid sampling at approximately 100 points on the catchment, the Wentworth method of measuring the average distance between contours along the same vertical and horizontal grid lines (which is a simplified way of estimating the total contour length over the catchment) and finally the hypsometric curve of cumulative area plotted against cumulative height. All three indices are naturally highly correlated with each other and less so with S1085, the main channel slope. Regression analysis however has shown that whilst overland slope, particularly the hypsometric curve, can aid prediction of percentage runoff and Tp to a lesser extent, the improvement is not enough to justify the labour of extraction. It is possible however that improvement of the model will eventually lead to the introduction of overland slope.

Small catchments

It has become apparent that the Flood Studies Report techniques are unable to predict floods on small ungauged catchments as well as they do for larger catchments. A regression study of small catchments has shown that the existing prediction equations for percentage runoff and unit hydrograph time-to-peak are equally applicable to all catchments regardless of size but that the errors of estimation increase for small catchments of less than 20 km^2. As shown in Figure 35, the relationship between the T-year return period flood on small catchments is the same as for larger areas. This work has pointed to the need for more data from small catchments representative of particular soils, geologies, land uses and climates in various parts of the country. Their minor importance for resource assessment or operation may make it difficult to justify widespread gauging of such small catchments (except in a few relatively isolated cases), but as greater confidence in design of structures, channel improvement works and flood forecasting is called for, such a collection of data seems to be essential. Discussions with central government departments and water authorities

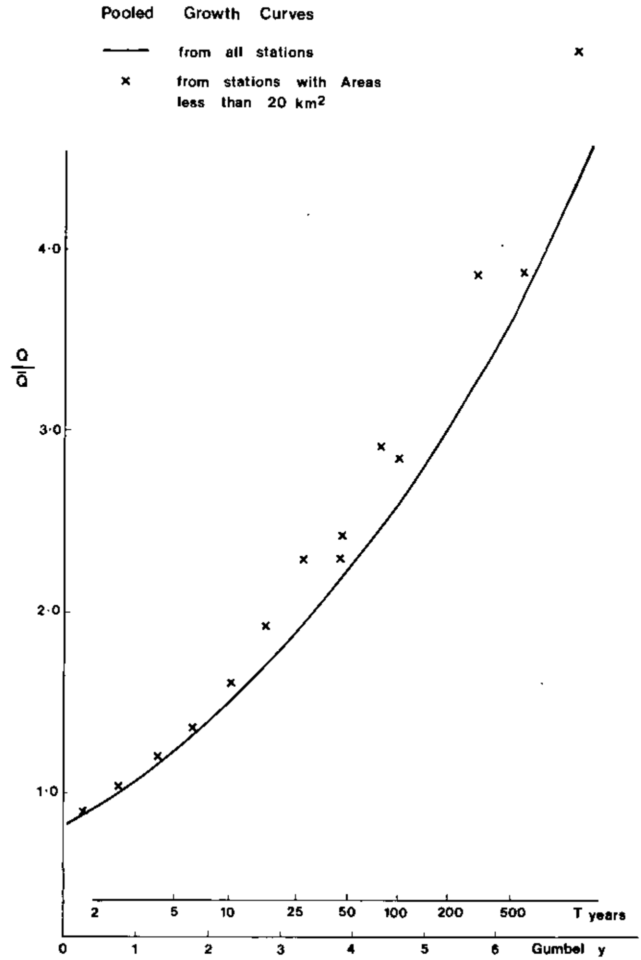


Figure 35. *Relationship between T-year flood and catchment area*

are now underway to see how such a programme of selection and instrumentation of a network of representative small catchments can best be organised.

Seasonal flooding

A method is being developed which will enable the user to calculate a flood frequency relationship for any group of months. Thus an agriculturalist might wish to know the probability of flooding during the growing season (say April—October) while a contractor might be interested in the probability of floods occuring while he is working in the river bed. Because of the many variations possible in the seasonal pattern of flooding, for example, the time of most frequent flooding or the differences between summer and winter flood frequencies and the many catchment effects on this pattern, the first stage is to assemble the available data into groups of stations with similar patterns.

Floods and tides

In the upper reaches of estuaries very high water levels are the result of interaction between high tides at sea and high flows in the river. While much is known of the statistics of river flows and of sea levels, the difficult problem of calculating the statistics of water levels at a point affected by both is largely unsolved. Several methods are being used to derive these statistics:

(i) by time series analysis of both tides and river flows

(ii) by using the entire distribution of high tides and of river flows (the later is the flow duration curve)

(iii) by an adjustment to annual maximum statistics of tides and flows.

The aim is to produce a method which can be used with whatever data are available to predict the frequency of high water levels in these stretches of rivers.

Historical floods

A search has been carried out for information in old records, journals and so on of flooding on chalk catchments. A large amount of material was collected, and although most of it was not of a quantitative nature, it appears that flooding on chalk is no more or less frequent than the few gauged records available suggest. There was considerable evidence for severe small scale surface flooding due to thunderstorms on chalk areas.

River Dee real-time forecasting system

Working under contract to the Water Research Centre, the Institute developed a rainfall-runoff model for use with the comprehensive telemetry network operating in the Dee catchment. Measured and forecast rainfall is input to the subcatchment model in which the catchment is conceived as a reservoir and which assumes a unique relationship between discharge (telemetered) and the remaining storage. Future storage changes are determined by the rainfall (suitably lagged) and hence future discharges may be predicted. Ungauged runoff is estimated from the nearest gauged subcatchment.

Runoff from gauged and ungauged areas is added, routed through reservoirs, and 'shifted' down tributary reaches (Alwen and Tryweryn) by a simple time-offset routing to an entry point on the main channel.

Main channel routing (between Bala and Manley Hall) is done by a model developed at the Hydraulics Research Station (Lowing, Price and Harvey, 1975), which reflects the large variation in travel times between high and low flows. Below Manley Hall, the lower Dee is modelled as a pair of linear reservoirs plus a constant lag. Lake levels or flow hydrographs are predicted up to 24 hours ahead at many points throughout the system and are available for display on a television monitor at the Bala control centre. Sophisticated data handling and display packages (some provided by Plessey Radar, who also built the data acquisition software) allow for the comparison of previous predictions and observations, alternative predictions based on different rainfall, forecasts or release sequences, and switch between radar and telemetered rain data.

A study of subcatchment model predictions indicates that good precipitation forecasts are more important in producing accurate flow prediction than recorded rainfall which has fallen over the subcatchment more than one or two hours in the past. This is because the small, steep upland subcatchments of the Dee have relatively short lag times (0·5 to 2·5 hours)—any rainfall which has fallen up to the lag time is already in the river system and has been recorded at a flow measuring station. Good quantitative precipitation forecasts are, for the Dee at least, fundamental to flood prediction on the subcatchments.

Improvements to the hydrological model are currently under investigation. It seems that a more flexible relationship to the storage-outflow relationship (a table of values relating storage parameter values to discharge) is preferable to a fixed parameter model. There is also some benefit gained by introducing a time-area diagram concept to the model's rainfall input. The original assumption here was that the rainfall for the model prediction at time T was that occurring at time $T-L$ in the past, where L is the catchment lag. The simple time-area diagram concept now preferred gives the rainfall input equal to:

$$0{\cdot}2R_{(T-L-1)} + 0{\cdot}6R_{(T-L)} + 0{\cdot}2R_{(T-L+2)}$$

This flexibility in the lag allows for the variation in travel time of rainfall to the outlet from different parts of the catchment. In practice, this produces a smoother hydrograph.

A new set of parameters has been developed and installed for the channel routing model which gives improved predictions of travel time along the two reaches of the main river from Bala to Corwen and from Corwen to Manley Hall.

Urban hydrology

Work is continuing on an investigation into rainfall-runoff relationships for partially and fully urbanised catchments. The research programme has two main objectives. The first is geared to the requirements of storm sewer designers. Rainfall-runoff data have been collected in a number of subcatchments in Bracknell, Southampton, Stevenage and Wallingford. This data collection exercise has been made possible by the development of the IH gulley meter (Blyth and Kidd, 1977), a photograph of which is shown in Figure 36. Data from these experiments are being used to calibrate a mathematical model for the simulation of the inlet hydrograph to the sewer system. Preliminary analyses have already been presented and further progress resulted from an International Workshop held at the Institute in April, 1978. Meanwhile, the archive of existing urban hydrological data from larger sewered catchments, which is being compiled at IH, has

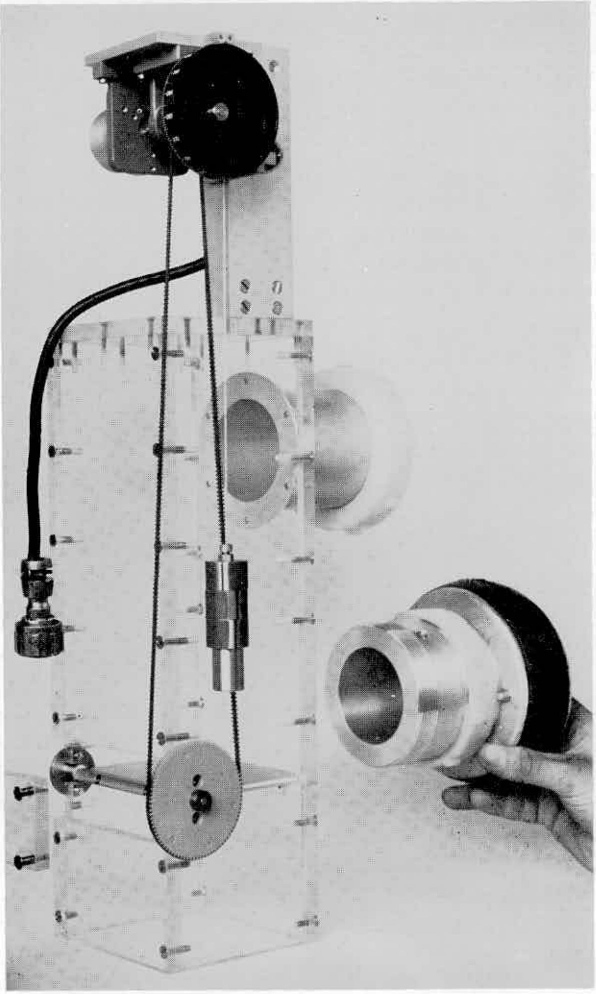


Figure 36. *The IH gully meter*

been employed to generate a regression model for the prediction of runoff volume for a given rainfall event. The final model will be incorporated in a design method currently under development at IH and the Hydraulics Research Station. This design method is part of a design package to be incorporated in the Manual of Good Working Practice currently being prepared by the DOE/NWC Working Party on the Hydraulic Design of Storm Sewers.

The second objective is the development of improved recommendations on the design of flood alleviation works in larger catchments subject to urban development. Preliminary recommendations are available as is a review of current design methods used to account for the effects of progressive urbanisation (Packman, 1977).

Automatic dilution gauging in storm sewers Manual dilution gauging in natural rivers is well-established at the Institute as described elsewhere in this Report. The technique has been adapted for use in storm sewers where, because high flow rates tend to be short-lived, the accent is on the development of an *automatic* technique whereby the instrumentation is triggered by a depth of flow above some pre-set threshold.

The instrumentation development is essentially complete and incorporates vacuum samplers operating at 2½ minute intervals and a Mariotte constant injection bottle. Sodium iodide was unsuitable as a tracer because of adsorption on to particulate matter in the flow, and lithium chloride is now used instead. Gilman (1976) has produced a method of estimating the errors incurred due to gauging in varying flow, and it has been found that, as long as the gauging reach is not too long, errors due to this source are not high.

Two sets of equipment have been installed at Bracknell and Stevenage, where there are standing-wave flumes, as a check on the validity of the dilution gauging results. When these systems have been proved, they will be installed in other sites to derive stage-discharge ratings at sites where no flow-gauging structure is possible.

Regional low flow characteristics

This investigation, to develop procedures for estimating low flows at ungauged locations, is being financed by the Department of the Environment. The 1974–6 research report outlined the large scale data gathering and analysis programme then underway. This has now been completed and flow duration (FDC) and flow frequency curves may be estimated from catchment characteristics for any river in the United Kingdom.

The development of relationships between catchment characteristics and low flows of a given frequency and duration divide into three aspects:

a Multiple linear regression relating the primary low flow indices (the 95 percentile excedance 10 day flow from the flow duration curve, and the two-year return period 10 day flow from the flow frequency curve) to numerical characteristics indexing size, slope, climate and geology of the catchment;

b Formulae linking the 10 day flow of the given frequency, eg. 95 percentile from the FDC to the *D* day flow of the same frequency;

c Formulae linking the *D* day flow of the given frequency with the *D* day flow of other frequencies, eg. the 99 percentile on the FDC.

A major component of the research concerned the numerical indexing of catchment geology. This was done by developing an objective method for calculating the proportion of base flow from river flow data and then relating this index to solid and drift geology. Relationships between base flow index (BFI) and geology are to be published on a regional basis for the UK. Approximate estimates of BFI can be made using Table 6 which shows typical values of BFI for a given drift-free solid geology. Figure 37 taken from the Thames basin report, exemplifies further refinements and shows how

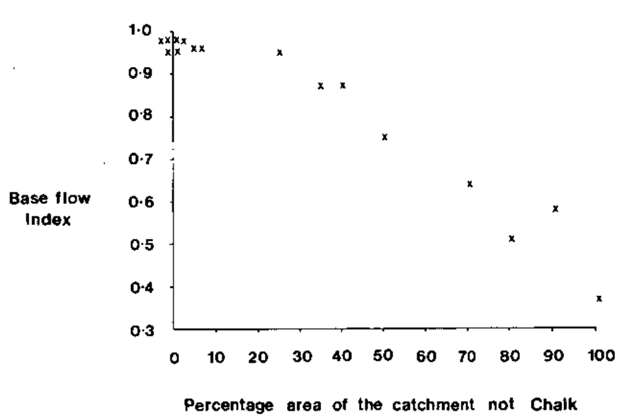


Figure 37. *Relationship between base flow index and solid geology for chalk catchments in the Thames basin*

the BFI of a catchment having a mixture of Chalk and Eocene solid geology can be estimated.

The applications of this research are illustrated

Permeability Characteristics	Storage Characteristics	Example of rock type	Typical BFI
Fissure permeability	Low storage	Carboniferous Limestone, Millstone Grit	·29
	High storage	Chalk	·95
		Oolites	·84
Intergranular permeability	Low storage	Hastings Beds, Coal Measures	·44
	High storage	Permo Triassic Sandstone	·74
Impermeable	Low storage at shallow depth	Lias	·51
		Old Red Sandstone	·52
		Silurian/ Ordovician	·40
		Metamorphic-Igneous	·41
	No storage	Oxford Clay, Weald Clay, London Clay	·30

Table 6. *Typical base flow indices for various rock types*

using the River Pang, a right bank tributary of the Thames draining a mainly chalk catchment. The estimation procedures for flow duration and flow frequency curves are broadly similar and the former is described here. A regression equation is used to estimate the primary low flow index, and for the Pang catchment is

$$\sqrt{Q95(10)} = 8{\cdot}51\ \sqrt{BFI} + {\cdot}0211\ \sqrt{L} - 1{\cdot}91$$

where: Q95(10) is the 10 day 95 percentile flow expressed as a percentage of the average daily flow (ADF),
BFI is the Base Flow Index estimated from catchment geology,
L is the mainstream length in km calculated from the 1:25000 scale map.

The estimation equation is one of several developed for different regions of the country based upon the data from a total of 517 catchments. The square root transformation was adopted as the compromise transformation that best normalised the variables used. Substituting the values for the Pang, $BFI = 0\cdot90, L = 26\cdot9$ km, Q95(10) is thus found to be 39·3% ADF.

A 'duration' relationship is then used to estimate the 95 percentile for other durations Q95(*D*) based on catchment rainfall and the value of Q95(10).

The next step in the procedure is to estimate the discharge of some other frequency, eg. Q99. This is performed using one of the 'type curves' from Figure 38 where the curve to use depends on the value of Q95.

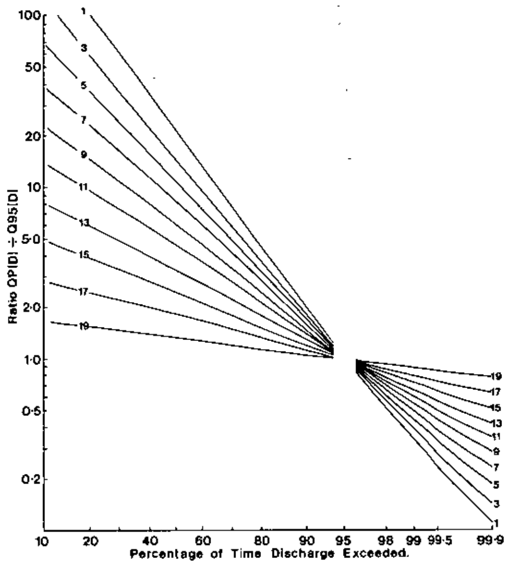


Figure 38. *Type curves and frequency relationship for flow duration curve*

The ratio *r* of the discharge of the required frequency *QP*(*D*) to Q95(*D*) can then be read from Figure 38 and the discharge at the new frequency calculated. The final step in the procedure involves a conversion of the discharge expressed as a percentage of average daily flow to a discharge in cumecs using catchment rainfall and evaporation data.

For the case where D = 30 days, Q95(30) = 39·9% (from the duration relationship) and the appropriate type curve (TC) to use for the frequency relationship is calculated from this value of Q95(30) by:

$$TC = \text{nearest integer} \left[10 \log 39{\cdot}9 \right] = 16$$

to give a ratio r of 0·8 to apply to Q95(30). Thus Q99(30) = 31·9% ADF. Procedures for estimating ADF in cumecs are given in the study reports.

River basin manuals, giving maps and methods for estimating BFI in a particular region, are being produced as part of a Low Flow Study series and are available from the Institute of Hydrology library. The initial issue includes the main study report, programmed learning manuals for estimating flow duration and flow frequency curves and some basin monographs.

Further issues covering the results of generalising other low flow measures to ungauged locations will be made as they become available. These other measures include the length of time the river spends below a threshold discharge, the storage required to maintain a given yield and the rate of river recession. New research topics include low flow forecasting and an investigation into low flow measures more appropriate to water quality where a low concentration of pollution, if extended over a sufficient duration, will be as severe as a greater concentration over a short period.

Other activities during the study involved a preliminary assessment of the severity of the 1976 drought using flow frequency analysis for nine rivers in the UK. The return period of the drought was found to vary with the duration of the low flow period being considered and the location of the catchment; most return periods in England and Wales were estimated at between 20 and 50 years.

Water resources

The growing demand for specialised hydrological analysis by consulting engineers, especially on overseas projects in the more arid regions of the world, provided the stimulus for building up an experienced group of both hydrologists and hydrogeologists able to apply the expertise of the Institute to the solution of engineering problems.

When accepting invitations to provide a consulting service, problems with an element of originality are sought, together with opportunities to apply research techniques developed by the Institute. In this way, the consulting work can be seen as complementary to research; novel applications provide a feedback and stimulus to further research while the quality of the practical answers provided is commensurate with the complexity of modern engineering and economic studies.

One particular strength of the present group is the interaction between the surface and groundwater aspects of regional water resource problems, particularly in the context of water supply. This experience, developed during the study of Northern Oman, has been invaluable in several recent studies in Sudan and Somalia.

Stochastic simulation models

Prediction of the future levels of the Dead Sea, as part of an investigation related to the Arab Potash Project[1]*, provided a test of several alternative simulation techniques. Long sequences of historic data were available; 116 years of annual rainfall at Jerusalem, broadly representative of the catchment area of the Dead Sea, were matched by a record of sea level changes based partly on observed data and partly inferred from indirect evidence. As the design of dykes and brine intake levels is dependent on the cumulative change in level over a time horizon of up to 30 years, the longer term trends in rainfall and sea level were more important than accurate prediction of the annual changes themselves.

Direct simulation of sea level changes using an autoregressive moving average (ARMA) model was based on the 30 years of observed sea levels, which had a lower variance and showed less persistence than the longer but less reliable record. Thus the predicted levels tended to be conservative compared with those generated by a similar model applied to the longer rainfall sequence, the synthetic sequences of rainfalls being transformed to sea level changes by an empirical relationship based on the historic records. In each case, the likelihood of future rises and falls in sea level could be estimated from a large number of simulations.

* Superscripts refer to list of projects given on page 93

While some of the long-term movements in the Jerusalem rainfall record could represent non-homogeneity through the combination of data from several different gauges over the years, it was assumed that the observed trends were real. This presented some problems in defining the most appropriate empirical relationship between rainfall and sea level change. Several models were tried, including one that attempted to give equal weight to the estimation of annual changes and the longer term trends. But comparative tests showed that a simple model could explain almost as much of the initial variance of the data as the more complicated alternatives.

Another example of the use of simulation models arose during several studies of some tributaries of the Nile, [2,3], when long flow sequences were required for reservoir operation studies. Here a multivariate lag-one Markov model was used for several tributaries and fitted to the periods of concurrent record. Simulations were developed from the longer records at other stations on the tributaries or on the main Nile. While the results were broadly satisfactory for the immediate problems, difficulties in the use of these methods were highlighted. In one case, certain operating decisions for the reservoir were highly dependent on a particular characteristic of the simulated record—one which was not directly involved in the simulation procedure; in another case, overbank flooding causing substantial attenuation of the seasonal flood peak led to apparent inconsistences in the correlation matrices. Another problem affecting these simulations was the frequency of zero flow during the latter part of the dry season. These zero flows disrupted the serial correlation between years and were overcome only by lumping several 10-day or monthly time periods together.

From these and the Dead Sea sudies, many topics for further research have been defined and the data will be reprocessed to test the application of alternative simulation models.

Flood Studies Report applications

All feasibility studies for dams require estimates of a design flood for the spillway together with estimates of the more frequent floods for design of the temporary works or for programming the construction to avoid periods of high flood risk. While the latter can often be estimated directly from the known flood flows in a historic record, should it exist at a relevant site, the former usually requires considerable study incorporating estimates of probable maximum precipitation (PMP) and hydrograph analysis.

Despite the many alternative approaches that are possible for estimating the design flood, the choice is dictated by the availability of data and the kind of estimate required. The Flood Studies Report provides a consistent framework within which the most promising approach can be developed. Inevitably, the range of environments covered by the overseas studies does not allow the direct application of the regional curves and empirical relationships developed in the report. However, the continuing acquisition of data and experience of these environments should eventually provide a basis for the derivation of similar regional equations.

Recent experience has covered several areas of Nigeria,[4,5,6] and also Morocco[7]. In these studies, the unit hydrograph/losses model was used to convert estimates of the probable maximum flood (PMF). In Nigeria, the PMP was based on specially commissioned work by the Meteorological Office, and the parameters of the model estimated from the available rainfall and runoff data and catchment characteristics. In Morocco where fewer data were available, the model parameters were adjusted to fit the predictions to a regional flood growth curve at low return periods; the PMP was estimated from daily data at two stations using Hershfield's method.

Regional analysis

In areas where specific engineering projects are not yet defined or where short runoff records are available for a number of rivers around the specific project location, techniques of regional analysis can lead to more reliable estimates of the potential resource than would be achieved by strictly local studies. Several examples of this nature have been tackled recently.

In Eastern Botswana[8] an estimate of the resources at all potential dam sites was required in order to define projects worthy of further study. The distribution of mean annual rainfall could be defined fairly well from existing records but runoff records were relatively short and available from only a few stations. Using all the records, regional curves relating mean annual runoff to rainfall could be derived and used to estimate mean annual runoff at any reservoir site. The variability of annual runoff, and specifically the drought flows of a given frequency, were based on dimensionless frequency curves derived from adjacent areas of southern Africa, a procedure which was tested using the longest of the available records.

In two major basins in Nigeria, the Gongola[6] and the Kaduna[9], where soil type and vegetation varied significantly over the large catchment areas, records from several stations within each basin were used to relate runoff to these catchment characteristics, together with catchment area, slope and rainfall. Using these relationships, runoff at any point in the basin could be derived from information available on maps. This form of analysis can be taken further to include flood parameters such as the mean annual one-day flood.

In the case of a number of smaller rivers where dams were required for local water supplies[4,5], the variation in catchment characteristics was less important. Nevertheless, the short period of flow records of uncertain quality meant that pooling rainfall and runoff data from several catchments, including some of no direct interest, provided a basis for deriving a reasonably reliable rainfall-runoff relationship. This could then be used to generate synthetic sequences of runoff data from the longer rainfall records.

Modern techniques in groundwater studies

The interpretation of borehole logs and pumping tests is common to most groundwater studies, yet aquifers are invariably so heterogeneous that the estimation of aquifer properties is still empirical. This is especially true when historic pumping test data suggest that tests were not carried out rigorously or were limited in scope. The background research into these problems continues; in particular, computing methods are being developed to achieve a more objective assessment of the data.

Other techniques, such as detailed studies of the hydrochemistry and isotopic content of groundwater, are being used more and more frequently to help identify the physical processes involved in groundwater movement and particularly in recharge of alluvial aquifers.

Currently, problems in groundwater development are being tackled in Mogadishu[10] and the Seychelles[11]. In the former, geophysical studies are being used to help identify the most promising areas for further exploration; studies of the flows of the River Schebelli will help in identifying the recharge pattern. In the latter a major drilling programme in the plateau sands is being supported by stream gauging and rainfall measurements in an appraisal of the regional groundwater resources. Hydrochemistry and isotope analysis will help identify the processes of groundwater recharge.

Studies of the groundwater potential of the alluvial fans on the south-eastern shore of the Dead Sea[1] are continuing as part of the development of the Arab Potash Project. Initial estimates were made from an appraisal of existing data from a few scattered wells and records of surface water flows. A preliminary groundwater flow net defined suitable areas for exploratory drilling.

Other water resource studies

Many studies are *ad-hoc* in the sense that the unusual character of the study area or the severe lack of data means that solutions must be developed from diverse information. In these cases it is useful to try to build up a model of the hydrological processes involved and this can often be done by analogy with other areas of similar climate and geology elsewhere in the world.

A recent study [12] to assess the yield of a wellfield in the Khor Arbaat which provides the water supply for Port Sudan illustrates the problems of using few relatively poor quality data. Briefly, the 4200 km² catchment of the khor drains part of the Red Sea hills in eastern Sudan. Rainfall is seasonal and falls as local storms producing short duration floods. The wellfield is in a small alluvial aquifer between two narrow gorges where the alluvium is relatively shallow. The floods cause some recharge of the aquifer but the major input is from the recharge of baseflows on the surface, arising from alluvial or hardrock storages upstream. Estimates of aquifer transmissivity from the limited pumping test data together with groundwater levels and gradients showed that it was unlikely that groundwater inputs or outputs from the aquifer were at all significant.

By modelling the upstream storage conceptually using the short period of observed baseflows it was possible to extend the baseflow record to the duration of the longer record of floods. A short record of detailed water level fluctuations in the vicinity of the wellfield made it possible to estimate the storage coefficient of the alluvium by water balance during periods when no floods occurred; the infiltration capacity of the gravels could then be estimated during periods when there were known volumes of flood flow.

These preliminary analyses which defined the aquifer characteristics allowed the construction of a simple operational model of the aquifer. The sequence of floods and baseflows could be fed into the model leading to an estimate of the water level fluctuations that would occur for a given rate of abstraction from the wellfield.

An appraisal of the water resources of Oman[13] as part of the preparation of a three-year programme for irrigation development illustrated the value of looking at the hydrological processes to combine much diverse information presented in previous consultants' reports. By extrapolating detailed knowledge from one area of the country to similar regions, it was possible to draw useful conclusions on water resources and the effects of their further development.

The studies also concerned the detailed patterns of existing groundwater abstraction by aflaj and wells, examining the hydrological and hydrogeological controls on these traditional sources of supply and the constraints to modern development imposed by the unique characteristics of the agricultural communities which have developed around these ancient water sources. Various methods were proposed to increase the overall availability of water and to improve the reliability of irrigation supplies from the alluvial aquifers. Means of modifying aflaj hydrographs and ways of controlling flood flows to increase recharge of the aquifers were proposed.

Follow-up research

A number of overseas projects have contained interesting problems which justify further study since a deeper understanding of the physical processes involved would benefit future studies in similar environments. The Water Resources Survey of Northern Oman described in the previous research report provided several such problems. One concerning the nature of the alkaline springs is described elsewhere, another concerned the way in which aflaj—the underground tunnels used to tap groundwater and bring it to the surface some distance downstream—respond to the configuration of the water table and particularly to recharge from rainfall and floods. In this case, the general computer-based groundwater model is being adapted to test various hypotheses derived from knowledge of the aflaj flows over the period of the previous study.

Studies of the hydrochemistry of the Tehran basin, together with the further development of techniques of groundwater analysis and data handling, have developed from our water resources studies. Current research in groundwater modelling is described elsewhere in this report.

Some studies carried out between 1976 and 1978 referenced in the text

1. Arab Potash Project, Hydrological Studies for Sir Alexander Gibb & Partners.
2. Hydrology of the Nile in Sudan for Sir Alexander Gibb & Partners.
3. New Halfa Rehabilitation Scheme, Water Resources Studies for Agrar und Hydrotechnik.
4. Iseyin, Oke Iho and Ejigbo Water Supplies, Hydrological Studies for Scott Wilson Kirkpatrick & Partners.
5. Igbaja Water Supply, Hydrological Studies for

Scott Wilson Kirkpatrick & Partners.

6. Upper Benue Development—Phase 1, A review of hydrological data and analyses for the Gongola catchment to Numan for Parkman Consultants Ltd.
7. Barrage de Zerrar Sur L'Oued Ksob, Hydrological Studies for Sir Alexander Gibb & Partners.
8. A Reconnaissance Study for Major Surface Water Schemes in Eastern Botswana, Hydrology, for Sir Alexander Gibb & Partners.
9. A preliminary study of the runoff characteristics of the Kaduna Basin for Parkman Consultants Ltd.
10. Mogadishu Water Supply, Hydrogeological Studies, for Sir Alexander Gibb & Partners (Africa).
11. Groundwater studies in the Seychelles, for Ministry of Overseas Development.
12. Port Sudan Water Supply, a review of the hydrogeology and water resources of Khor Arbaat, for Sir Alexander Gibb & Partners (Africa).
13. A review of the water resources of Oman and the potential for their development for Turner Wright & Partners.

Overseas aid programmes—ODM funded projects

Measurement of monsoon recharge
Indo-British Betwa groundwater project

The Institute is responsible for the soil hydrology studies of the Betwa catchment within the overall context of a groundwater resources project currently being carried out by the IGS in partnership with the Indian Central Groundwater Board. The object of the study is to define the role of the soil in partitioning monsoon rainfall into either surface runoff or recharge to the aquifer.

Such information is important for the agricultural development of the area because the highly seasonal rainfall results in surplus moisture being available during the monsoon season, followed by a prolonged dry season when soil moisture storage is insufficient to support transpiration beyond a limited period. Preliminary estimates of the recharge situation have been made from water balance calculations based on analysis of existing rainfall, runoff and evaporation records. The mean annual rainfall over the basin is some 1140 mm, of which about 300 mm goes to surface runoff; potential evaporation, on the other hand, approaches 1700 mm, making it easy to understand why field investigations of the infiltration/storage mechanisms operating are crucial to long-term development plans.

The Betwa catchment is approximately 18,000 km^2 in area, situated between Jansi and Bhopal, about 400 to 600 km south of Delhi. Multiple flows of trap basalt occupying a pre-existing Vindhyan sandstone landscape form a basin of low relief, with subsidiary low hills composed of sandstone inliers and basalt outliers; the extreme north end of the catchment is underlain by granites. The predominant soil cover is a silty black cotton-soil derived from the erosion of the basalts. The water table lies generally between 2 and 11 metres deep in the weathered surface zone of the basalt, beneath the black cotton soil.

Figure 39. *Neutron probe in use on the Betwa project*

The soil investigation is divided into two stages. Stage one consists of establishing an extensive network of 30 or more neutron probe access tubes to establish the areal variability of the soil water storage conditions and the abstraction characterists of the principal vegetation of the black cotton soils—wheat and pulses. The network was established by the end of 1977 and observations will continue weekly for 12 months, subject to accessibility during the monsoon period.

The hydrogeological programme is as yet incomplete and there is little information concerning such matters as the number and extent of the basalt flows and the existence or otherwise of confined aquifers between the basalt flows. The amount of recharge and recharge mechanisms are as yet speculative, as is the relationship between the aquifers and the river system. However, results so far suggest that there is probably little recharge through the black cotton soils and that any source of major recharge may have to be sought elsewhere, for example in the Vindhyan sandstones or along their contacts with the basalts.

The second stage is to answer three questions posed by the hydrogeologists:

(1) How much water drains through the soil to the shallow unconfined groundwater aquifer during the monsoon period, June to September?

(2) How much water is lost from the aquifer by direct upward capillary flow during the dry season?

(3) Can the seasonal soil water content profiles be used to provide a good estimate of the specific yield of the various layers of the unsaturated zone and of the zone of annual fluctuation of the water table?

The scope of the study is limited by the fact that only two qualified members of staff are engaged in the project. Thus only 'representative' flow sites can be examined in detail for stage two, but the surprising uniformity of the soils justifies a fair degree of extrapolation. Tension profiles are to be monitored daily, in addition to the soil water content measurements, in order to provide the data necessary to compute water fluxes in the unsaturated zone. The stage two programme of at least 15 months duration will, if possible, be started in time to include the 1978 monsoon which begins in June.

One of the major water resources projects at present in progress in Sri Lanka is the diversion of water from the Mahaweli Ganga, the principal river of the island, to expand irrigation of paddy rice in the northern central area of the country. It is planned eventually to bring some 260,000 hectares of new land under irrigation, and to improve the availability of water during the dry season over a further 100,000 hectares of existing paddy lands. Diverted Mahaweli water is being transferred to the catchments of rivers which feed tanks (storage reservoirs) from which the paddy fields are irrigated. Several tanks within the Mahaweli Project area have storage capacities exceeding 1000 million m^3, and it is of interest that the bunds (dams) of these tanks were initially constructed in the 12th century A.D. or earlier, although most of the larger tanks subsequently fell into disuse and have only recently been fully rehabilitated by the Sri Lanka Irrigation Department.

As work has progressed with the Mahaweli Project, there has been concern that the efficiency of water use on the irrigated paddy areas has been too low for the full benefits of the project to be achieved, and a Water Management Division has recently been set up within the Irrigation Department to study, and where possible implement, more efficient methods of water use. To assist the work of the Water Management Division, a joint study has been started at Kaudulla Tank (storage capacity 128 million m^3, present irrigated area 4328 hectares) with the aims firstly of measuring the different water balance components for a typical tank-fed paddy area, and secondly of predicting potential savings in irrigation water which might result from the application of various alternative water management procedures.

The Kaudulla Study is being administered jointly by the Overseas Unit of the Hydraulics Research Station (HRS) at Wallingford and the Irrigation Department in Sri Lanka. The Institute was asked to provide assistance with hydrological aspects of the work, and HRS and IH have each provided a member to form the British team for the study. The main areas of interest for IH are the measurement of rainfall, the estimation of evaporation from both reservoir water surfaces and the cropped areas of paddy rice, the quantifying of seepage losses from the paddy fields and the relating of agricultural practices to water use over the growing season.

Kenya hydrology project

This ODM-financed project is concerned with the establishment of four representative basins in the Machakos-Kitui area of Kenya. Previous hydrological studies have concentrated on the well-watered, highly productive, volcanic soil areas but population pressure is such that increased agricultural exploitation of the drier medium potential areas, as exemplified by the Machakos and Kitui districts, will become necessary over the next decade.

The four basins are being instrumented to provide measurements of rainfall, evaporation, runoff, sediment discharge and soil moisture. Data from existing networks are being analysed and a model to relate crop yields to climatic variables is being developed.

Instrumentation

Automatic weather stations

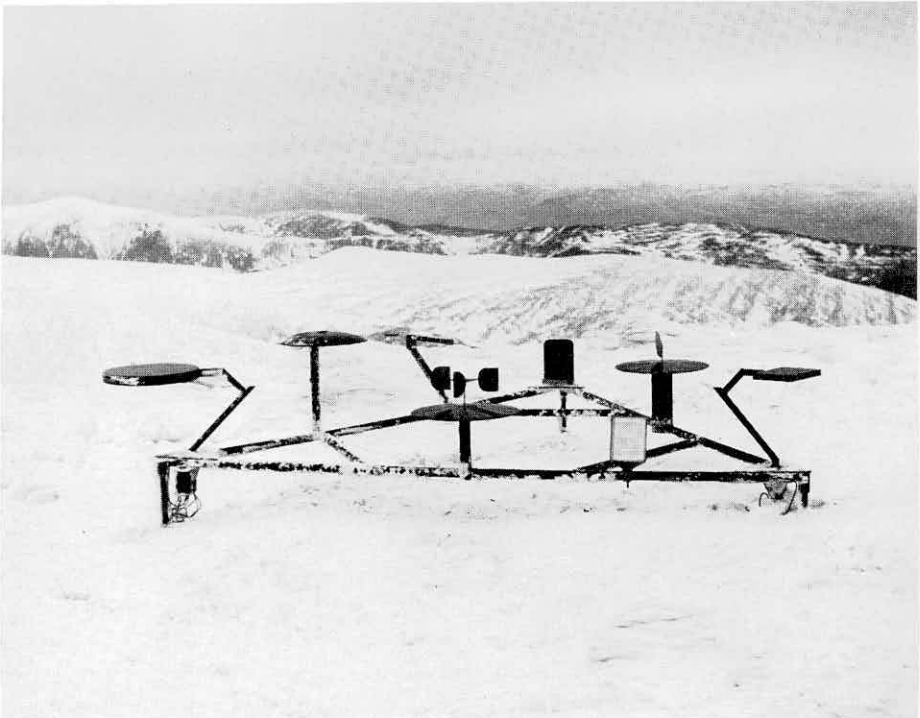
There are now 59 Institute-designed automatic weather stations in operation, 46 of which are installed in the UK. These stations serve the needs of both the Institute's own research projects and those of outside users, including contract work in other countries.

The Cairngorm project

This project is in three parts. First there is the experimental work concerned with extending the environment under which an Institute AWS will operate, in this case by exploring passive means such as the use of flexing and slippery surfaces to deter ice formation on the sensors (see Figure 40). Secondly, the Physics Department of Heriot-Watt University has designed and installed a mains powered sensor system housed in a cylinder which opens every half hour and exposes a wind speed, wind direction and air temperature sensor for 2½ minutes. Thirdly, data from both systems of sensors are telemetered on alternate hours by VHF radio from the stations on the summit of Cairngorm to a base station 14 km away at Aviemore and subsequently transmitted over the GPO telephone network to the Institute at Wallingford and to the Heriot-Watt University at Edinburgh.

Automatic weather stations for the Libyan Sahara

Complementary to the Cairngorm Project, is a project started recently in the Libyan Sahara desert at Sarir and Sebha, and in the semi-arid area around Benghàzi at El Marj for the Agricultural Research Centre and for FAO in Tripoli, who wish to measure the climate at several experimental irrigation sites (Figure 41). Among anticipated difficulties are effects of sand blasting and the problem of dust getting into or settling



on the sensors. Initial modifications to standard stations were the addition of solar power panels to the first four stations, an increase in the water container capacity for the wet bulb, and the design of a new method of housing the logging system below ground to protect it from the intense heat.

Figure 40. *The Institute's experimental low profile weather station on Cairngorm showing some of the earlier experimental ice-deterring sensor designs*

The Tietê River telemetry project, Brazil

IH has been engaged as consultants to Consôrcio Nacional de Engenheiros Consultores, São Paulo, Brazil, to advise on the choice and specification of a telemetry system for the Tietê River Basin, a catchment of about 50,000 km^2 extending from São Paulo to the Paraná River. The requirement was to find a suitable system, preferably Brazilian, capable of telemetering measurements of river level and rainfall as well as flow and level data from six dams, by VHF and UHF radio, to a central station where the data would be

Figure 41. *Future weather station site in the Libyan Sahara showing early phase of installation of irrigation pump and pipes*

input to a computer programmed with a rainfall-runoff model. The purpose of this was to forecast dam levels sufficiently far in advance for effective control of the river to avoid a repetition of the damage to dams which occurred in 1976.

Simple instruments for use overseas

The design philosophy here is to develop instruments costing very little to make and requiring no maintenance but nevertheless using the very latest microelectronic techniques. Concentrating first on a raingauge, traditional mechanical manufacturing techniques and materials have been replaced by experimental methods using moulded plastics, including polyurethane foams. The electronics comprise one printed circuit board, encapsulated in a transparent plastic, which incorporates both the solid state store and a Liquid Crystal Display; it is this that makes a simple, cheap, but sophisticated system practical, storing three months of daily totals.

Microprocessors

The potential application of microprocessors in hydrological instrumentation has been investigated in recent years. In cases such as eddy correlation equipment, microprocessors offer possibilities for making measurements which were previously impossible: for more conventional instruments the still relatively high power consumption of microprocessors limits their use to base or field office equipment. An example is the Cairngorm project where the microprocessor not only controls the telemetry system from base, calling up the remote mountain stations automatically, but also receives, stores, processes and then lists the data. It also holds a day's data for transmission over the GPO telephone network, using an acoustic coupler.

Another important use of microprocessors this year has been their development for use in reading and processing the data recorded by newly developed solid state loggers. The freedom and versatility that such a system offers, as compared to that of a larger computer of the pre-microprocessor era, is that data from solid state stores (or from Microdata logger tapes) can be read and processed by a comparatively cheap and compact device installed in field offices, or at the base station of a remote overseas project, giving rapid results to the user. This ready access does not prevent the data from being input to a larger computer for storage in a central bank, for more general availability and for transcription to seven-track tape for wider distribution.

Solid state logging

The bulk of Institute AWS data, and the wide variety of other hydrometeorological measurements, are currently recorded by means of the Microdata logging system which is now a well established and reliable system backed by a large amount of hardware, and by computer software for both the PDP8 and Univac; it is not likely, therefore, to fall rapidly into disuse. However, with the development and commercial availability of the new integrated circuit solid state stores and microprocessors, new and dramatic possibilities are opened up for data logging. As yet the capacity of the stores is much less than that of a C60 cassette (2000 as compared with 56,000 8-bit words). But even today their capacity is sufficient to make them very attractive as an alternative to tape and their capacity is increasing rapidly as the technology advances.

The small capacity is largely overcome by data reduction in an interface unit, prior to storage. This unit produces hourly means and totals of all the variables, removing the need for five minute records as in standard Institute AWS. The first device to be developed was a solid state raingauge using the Rimco gauge as sensor. This can store 256, 8-bit, words, i.e., 256 daily totals of rain or a month of three hourly totals. Ten of these are now in operation. A prototype automatic weather station using the same stores, one store per channel, has been in operation at Wallingford for a year, and five more are now being produced. They operate for 10 days recording hourly values. One disadvantage is that the store must be continuously powered by batteries, but a design is now being evolved using the more recent type of store which do not require power to hold the data, simply to write it.

Water level instruments

The level sensor, as described in previous annual reports, is now in use at all of the Institute's main river gauging sites using the Microdata logging system.

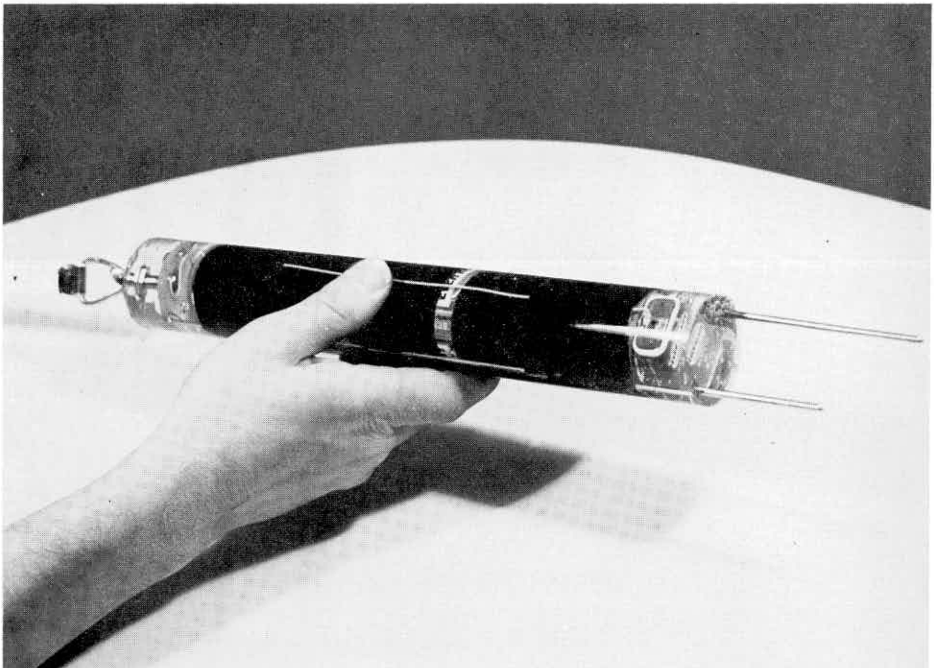
This year a simplified model of the sensor was designed using a single potentiometer instead of the three of the standard instrument. It is intended for situations where the range and discrimination of the 3 potentiometer-type would be wasted, e.g. in urban work where ranges are small, or where fine discrimination is not vital. The one-channel nature of the sensor makes it particularly suited for use with new solid state loggers.

A development based on an instrument which has been in use at Plynlimon for several years is a probe used to detect water levels in flumes and stilling wells. It gives a visible indication when the probe contacts the surface. The new version shown in Figure 42 is of cheap throw-away, moulded plastic construction; it lasts just as long as the batteries, and being totally encapsulated, it is not damaged by submersion or rough handling in the field.

Eddy correlation instrumentation

An important stage in the Institute's studies of evaporation is the development of an instrument capable of making spot measurements of evaporative loss. As reported earlier in the Hydrological Processes section of this report, the eddy correlation technique seems to show most promise. Instrument development work so far includes the production of (1) a heat-pulse generator for testing the temperature sensors, (2) a three-dimensional anemometer, including its helicoids, and (3) the electronic and mechanical means of detecting the speed and direction of rotation of the helicoids. The wind speed measurements, together with those from the temperature and humidity sensors,

Figure 42. *Very cheap encapsulated probe for measuring water levels in flumes and stilling wells*



are fed into a microprocessor 20 times a second for rapid processing in real time to give actual evaporation.

Publications and References

Anon., 1976. Water balance of the headwater catchments of the Wye and Severn, 1970–1975. *Inst. Hydrol., Wallingford, Rep. 33.*

The analyses described in this report show that the mean annual loss (1970–1975) for the Wye catchment is 18% of the mean annual precipitation of 2415 mm. The mean annual loss from the Severn catchment, adjusted to allow for the unforested area in its upper reaches, is about 38% of the mean annual precipitation of 2388 mm.

Anon., 1977. Selected measurement techniques in use at Plynlimon experimental catchments. *Inst. Hydrol., Wallingford, Rep. 43.*

The nature of the Plynlimon experiment and the physical conditions prevailing have led to the adaptation of standard instruments and the design of new ones. This report deals with measuring devices for rainfall at both ground and canopy level, throughfall and stemflow beneath the forest canopy, snowmelt, and streamflow from small sources. The emphasis is on instrument design and operation, not theory.

Bell, F.C., 1976. The areal reduction factor in rainfall frequency estimation. *Inst. Hydrol., Wallingford, Rep. 35.*

Details of work carried out to re-evaluate and check the areal reduction factors contained in the Flood Studies Report including calculating areal and point rainfalls for various durations and United Kingdom locations which permit a direct estimate of ARF as the ratio of areal to point rainfall of the same return period.

Bell, J.P., 1976. Neutron probe practice. *Inst. Hydrol., Wallingford, Rep. 19 (2nd edit.).*

A basic guide to the practical use of the neutron probe, its working principles and some of its applications to help the user avoid the mistakes and frustrations commonly encountered by those new to the field. Properly used and understood the neutron probe can provide *in situ* measurements of soil moisture change to a precision obtainable in no other way.

Beran, M.A. and Gustard, A., 1977. A study into the low-flow characteristics of British rivers. *J. Hydrol., 35: 147–157.*

This paper describes investigations into methods for predicting low flows from catchment characteristics. Different sources of errors in flow data are described which are all taken into account when selecting suitable flow records for analysis. A number of analytical techniques which incorporate both the magnitude and duration of low flows are described and some of their areas of application given.

Beran, M.A. and Nozdryn-Plotnicki, M.J., 1977. Estimation of low return period floods. *Hydrol. Sci. Bull., 22 (6): 275–282.*

A method was sought for estimating low return period floods (0·2–5 years) from annual maximum data. The theoretical relationship between the peak over threshold and annual maximum return periods is reexamined and an empirical relationship based upon United Kingdom flood data is proposed.

Calder, I.R., 1977. A model of transpiration and interception loss from a spruce forest in Plynlimon, central Wales. *J. Hydrol., 33: 247–265.*

A model of evaporation loss (interception plus transpiration) from a spruce forest, based on the Penman-Monteith equation, is derived from lysimeter and automatic weather station data.

Calder, I.R., 1978. Transpiration observations from a spruce forest and comparisons with predictions from an evaporation model. *J. Hydrol., 38: 33–47.*

Neutron probe and lysimeter techniques were used to investigate further the transpiration response of spruce forest to changing environmental variables and to test the operation of a previously proposed model of evaporation.

Curran, J.C. *et al.*, 1977. Cairngorm summit automatic weather station. *Weather, 32, 60–63.*

A description of a co-operative project between Heriot-Watt and Edinburgh Universities, the Institute of Hydrology and the Meteorological Office to develop an automatic weather station capable of continuous operation in the sub-arctic conditions on the summit of Cairngorm (1245 m).

Douglas, J.R., Clarke, R.T. and Newton, S.G., 1976. The use of likelihood functions to fit conceptual models with more than one dependent variable. *J. Hydrol., 29: 181–198.*

Models of catchment behaviour usually express one output, or dependent variable, as a function of several inputs, or independent variables; streamflow is commonly the dependent variable and precipitation and evaporation are independent variables. Soil moisture may also be measured, however, and this may be regarded as a second dependent variable that is also a function of precipitation and evaporation. This paper describes work which had, as one objective, a study of the usefulness of available soil moisture records for assisting with model calibration. Incorporation of soil moisture data in the model calibration procedure was achieved by generalizing the commonly-used least squares criterion to a likelihood function, a generalization made at the expense of introducing further assumptions regarding the probability distribution of model residuals.

Farquharson, F.A.K. *et al.*, 1978. Estimation of runoff potential of river catchments from soil surveys. Soil Survey, Special Survey No. 11, Harpenden.

The hydrological classification from which the Soil Survey produced a map of winter rain acceptance potential (WRAP) for England and Wales. It gives an explanation of how the WRAP maps for the British Isles were prepared for Vol. V of the Flood Studies Report and how these maps can be used as an aid to estimating flood response of river catchments.

Gash, J.H.C. and Stewart, J.B., 1977. The evaporation from Thetford Forest during 1975. *J. Hydrol., 35: 385–396.*

Previous measurements of the surface resistance of a pine forest have been used in the Monteith version of the Penman equation, to obtain an estimate of

transpiration from automatic weather station data. This result, combined with measurements of the loss of water by evaporation of intercepted rainfall, has been used to provide a quantitative estimate of the evaporation from Thetford Forest during 1975.

Gash, J.H.C. An analytical model of rainfall interception by forest. *Q.J. Royal Met. Soc. (in press).*
The evaporation of intercepted rainfall depends on the duration of saturated canopy conditions, the mean evaporation rate during these periods, and the size of the canopy store and number of times it is emptied by drying out after rain. A model, conceptually similar to the Rutter model but replacing the numerical approach with an analysis of storm events, gives estimates of interception loss solely from rainfall measurements.

Gash, J.H.C. and Morton, A.J. An application of the Rutter model to the estimation of the interception loss from Thetford Forest. *J. Hydrol., 38: 49–58.*
Interception loss over 21 4-week periods during 1975–76, estimated using the Rutter model with data from an automatic weather station mounted above the canopy, was in good agreement with observed evaporation.

Gash, J.H.C., *et al.,* Evaporation from forests. *J. Inst. Wat. Engrs. and Sci., 32: 104–110.*
The limitations of catchment experiments for estimating the effects of afforestation on water resources are discussed; the importance of an appreciation of the enhanced rate of evaporation of rainfall intercepted by forests and of the stomatal controls on transpiration is stressed.

Gilman, K., 1977a. Dilution gauging on the recession limb: I. Constant rate injection method. *Hydrol. Sci. Bull., 22 (3): 353–69.*
Formulae are presented for the error arising in the case of a constant rate tracer injection, and examples are given of their application to results from a number of different flow systems. It is shown that the error may be significant in two situations: where the rate of change of discharge is high and where poor mixing necessitates long gauging reaches and hence long tracer injections.

Gilman, K., 1977b. Dilution gauging on the recession limb: 2. The integration method. *Hydrol. Sci. Bull.*, 22 *(4): 469–481.*

This paper extends the theory of the residence time model to the case of a dilution gauging by the integration method, and presents analogous formulae for the errors.

Gilman, K., 1977c. The hydrology of Thatcham reedbeds. *Inst. Hydrol., Wallingford, Rep. 37.*

Describes measurements made to follow the processes of water movement in the reedbeds and suggests management procedures which should minimise the damage caused to the wetland community by lowering of the water table associated with gravel extraction.

Gilman, K., 1977d. Movement of heat in soils. *Inst. Hydrol., Wallingford, Rep. 44.*

This report is a review of the large and varied literature on soil temperature. Its aim is to place the key literature in context and into a consistent structure.

Jones, D.A., 1978. Non-linear autoregressive processes. *Proc. Roy. Soc., London A., 360, 71–95.*

Models of the form $X_{n+1} = \lambda(X_n) + Z_{n+1}$ are considered for time-series $\{X_n\}_3$ where $\{Z_n\}$ is an impulse sequence and λ is a nonlinear function. These processes extend the range of behaviour available with linear autoregressive-moving average models. Methods for approximating the stationary distributions of the processes are considered and expressions are found by which the exact moments, joint moments and densities of stationary processes can be obtained. Moments and densities of conditional (predictive) distributions are also found. The results of these methods have been verified by computer simulations and these and other numerical results are given. The extension of the methods obtained to treat multivariate processes of the same form is indicated briefly.

Kidd, C.H.R. and Helliwell, P.R., 1977. Simulation of the inlet hydrograph for urban catchments. *J. Hydrol., 35: 159–172.*

A single nonlinear reservoir model is proposed as a realistic routing method for the above-ground phase of urban runoff. The use of the model is demonstrated on data collected from two very small (less than 1 ha) suburban catchments instrumented for this purpose. The shape of observed hydrographs is modelled satisfactorily using a nonlinear exponent of 2/3 and fitted routing constants.

Lowing, M.J., Price, R.K. and Harvey, R.A., 1975. Real-time conversion of rainfall to runoff for flow forecasting on the River Dee. *Weather Radar and Water Management, WRC Conf., Chester.*

Lowing, M.J., 1977. Urban hydrological modelling and catchment research in the United Kingdom. *Inst. Hydrol., Wallingford, Rep. 36.*

This report is a copy of Technical Memorandum No. IHP–4 of the American Resources Research Program, published in July 1976. It is the UK contribution to the state-of-the-art reports submitted to the Subgroup on the Hydrological Effects of Urbanisation set up as part of the UNESCO-sponsored International Hydrological Decade.

Moore, C.J., McNeil, D.D. and Shuttleworth, W.J., 1976. A review of existing eddy-correlation sensors. *Inst. Hydrol., Wallingford, Rep. 32.*

This report describes the results of a literature survey up to 1976 and makes recommendations on the priority to be assigned to the design and development of those sensors considered potentially useful to the development of simple eddy-correlation apparatus.

Moore, R.J. and Clarke, R.T. Some properties of variance reduction techniques where hydrological extremes are estimated by Monte Carlo simulation. *Wat. Resour. Res. (in press).*

Neal, C., 1977. The determination of adsorbed Na, K, Mg and Ca on sediments containing $CaCO_3$ and $MgCO_3$. *Clays and Clay Minerals, 25, 251–258.*

A method for the determination of the cations of Na, Km Mg and Ca adsorbed on clay minerals mixed with $CaCO_3$ and $MgCO_3$ is described. An ethanolic solution of LiCl–CsCl is used to displace the exchangeable cations. Blank determination performed using either a second ethanolic leach or a second LiCl–CsCl leach, are used to correct for carbonate dissolution. Details of the method's development are given.

Newson, M.D., 1976. Mapwork for flood studies. Part III: Analysis of indices and re-mapping. *Inst. Hydrol., Wallingford. Rep. 25.*

This report sets on record the principal climatic characteristics of rainfall at Plynlimon from 1968–1975 with particular attention to 'water-years' October 1973 to September 1975.

Newson, M.D., 1976. Mapwork for flood studies. Part III: Analysis of indices and re-mapping. *Inst. Hydrol., Wallingford. Rep. 25.*

Part I of this report covered the background to the selection of morphometric indices for use as independent variables in the U.K. Flood Study (NERC, 1975) and the derivation of values for those indices on 755 catchments in the British Isles. Part II now describes the interrelationships between variables, including those extra ones derived for unit hydrograph shape prediction, their re-mapping on national maps and their usefulness for flood prediction at ungauged sites.

Newson, M.D., 1976. Soil maps to predict catchment behaviour. *Welsh Soils Discussion Group Report 17, 174–193.*

Newson, M.D., 1976. Soil piping in upland Wales: a call for more information. *Cambria. 3 (1), 33–39.*

Newson, M.D. and Harrison, J.G., 1978. Channel studies in the Plynlimon experimental catchments. *Inst. Hydrol., Wallingford, Rep. 47.*

The report contains a collection of field observations on the classification, distribution, suggested origin, capacity and throughput characteristics of channels in the Plynlimon catchments. The fieldwork methods covered include mapwork, the use of channel cross-section device, dye tracing and dilution gauging. Four types of perennial surface channel are described, as well as ephemeral channels, soil pipes, 'flushes' and artificial drainage ditches. The open channels are investigated for relations between dimensions at the channel-full stage and catchment area.

O'Connell, P.E. *et al.*, 1977. Methods for evaluating the U.K. raingauge network. *Inst. Hydrol., Wallingford, Rep. 40.*

This report outlines some of the basic properties of rainfall and elementary network design. This is fol-

lowed by a literature review on raingauge network design and a review of user requirements. The methodology for both direct and indirect (i.e. rainfall/ runoff modelling) evaluation of the UK network is described, followed by suggestions for modifications to the existing network to meet current demands more efficiently.

Packman, J.C., 1977. The effects of urbanisation of flood discharges—discussion and recommended procedures. *Proc. Cranfield Conf.*

This paper discusses the effects of urbanisation and the requirements of flood estimation procedures. The Institute's research programme is outlined and recommended procedures are presented for adjusting the unit hydrograph and flood frequency techniques of the Flood Studies Report to account for urban development.

Potter, H.R., 1978. The use of historic records for the augmentation of hydrological data. *Inst. Hydrol., Wallingford, Rep. 46.*

Considerable hydrological information can be obtained from different kinds of historic records. This report describes a routine method for searching these records outlining the nature and value of the information that may be found, and some of the difficulties which may be encountered.

Roberts, J.M., 1977. The use of tree-cutting techniques in the study of the water relations of mature *Pinus sylvestris* L. I. The technique and survey of the results. *J. exp. Bot., 28 (104), 751–767.*

This paper gives a description of 'tree cutting' under water in an attempt to understand some of the basic problems concerning the water relations of trees.

Roberts, J.M. and Fourt, D.F., 1977. A small pressure chamber for use with plant leaves of small size. *Plant and Soil, 48, 545–546.*

A description of a pressure chamber for use with small leaves which can be constructed out of commercially available parts.

Roberts, J.M. Use of tree cutting technique in the study of the water relations of Norway Spruce, *Picea abies* (L) Karst. *J. exp Bot., 29: 465–471.*

The tree cutting technique was used on Norway spruce

in the Hafren forest, Mid-Wales. The relationship between stomatal resistance and atmospheric humidity in the experiment was similar to one derived from an independent optimization method for a forest lysimeter nearby. Transpiration estimates for the tree cutting method and the lysimeter were in reasonable agreement.

Shuttleworth, W.J., 1977. The exchange of wind-driven fog and mist between vegetation and the atmosphere. *Bound. Lay. Meteorol., 12, 463–489.*

This paper presents a one-dimensional description of the exchange of water between wind-driven fog and natural vegetation for two processes, the first involving direct capture of the fog droplets and the second involving exchange by the evaporation/condensation process.

Shuttleworth, W.J., 1977. A simplified one-dimensional theoretical description of the vegetation-atmosphere interaction. *Bound. Lay. Meteorol., 14, 3–27.*

This paper develops and simplifies analysis in an attempt to provide a more practical description. It is shown that the generalized combination equation devised by the author in a previous paper can be rewritten in a form which is identical to the Penman-Monteith equation in the single-source limit *providing* that the canopy resistance is redefined in two alternative ways, according to whether there is large-scale variation in surface wetness.

Smart, J.D.G., 1977. The design, operation and calibration of the permanent flow measurement structures in the Plynlimon experimental catchments. *Inst. Hydrol., Wallingford, Rep. 42.*

Descriptions and illustrations are provided for the major flow measurement structures on the Rivers Wye and Severn and their tributary streams. The dimensions quoted are according to design flow calculations. Both analogue and digital water-level recorders have been used. Field calibrations have been made by dilution gauging, current metering and volumetric gaugings as a check on the theoretical rating curves.

Smith, P.J., 1977. The numerical computation of streamflow and its error using the constant rate injection method of dilution gauging. *Inst. Hydrol., Wallingford, Rep. 38.*

This report describes an efficient procedure for computing the flow value and its error when using the constant rate injection technique of dilution gauging. The computation method proposed, by describing the error contribution from each part of the flow value calculation and revealing where such errors are systematic, allows the user to assess the validity of the gauging.

Stoneham, S.M. and Kidd, C.H.R., 1977. Prediction of runoff volume from fully-sewered urban catchments. *Inst. Hydrol., Wallingford, Rep. 41.*

This report describes the development of a mathematical model using regression analysis on existing urban catchment data, to predict the volume of runoff from a given rainfall event on a fully-sewered catchment. The model will ultimately be incorporated into a new design method for storm sewer systems.

Strangeways, I.C. and Curran, J.C., 1977. Meteorological measurements under conditions of icing: some new attempts to solve the problem. *WMO Technical Conference on Instruments and Methods of Observation (TICIMO), Hamburg.*

Sutcliffe, J.V., 1978. Methods of flood estimation: a guide to the Flood Studies Report. *Inst. Hydrol., Wallingford, Rep. 49.*

Templeman, R.F., 1978. The translation of Microdata style automatic weather station data. *Inst. Hydrol., Wallingford, Rep. 48.*

This report describes the software available for processing cassettes containing data recorded on Microdata loggers by the Institute's automatic weather stations.

Turner, M. and Brunsden, G.P. Solid state recorder for rainfall measurement. *IAHS Bulletin (in press).*

Truesdale, V.W. *et al.*, 1977. Transformation and decomposition of ß-molybdosilicic acid. *Analyst, 102 (1211).*

This paper shows that the mechanism for the transformation of β-molybdosilic acid consists of a unimolecular transformation of the β^{4-} ion, with an acid-base pre-equilibrium involving the βH^{3-} species.

The system has been studied at pHs between 0·0 and 4·0, sodium chloride concentrations of 0·0 and 1·0M and molybdate-molybdenum concentrations between 0·005 and 0·050M. The information relates directly to the conditions used by most workers who analyse natural waters for silicate-silicon.

Truesdale, V.W., 1977. Iodine in inshore and off-shore marine waters. *Mar. Chem., 6, 1–13:*

The temporal variation of iodate and total iodine in the Menai Straits and Irish Sea is discussed together with station data for the Atlantic Ocean. Surprisingly little temporal variation was found in either iodate or total iodine even though seasonal nutrient cycling occurred within these water bodies.

Vachaud, G. *et al.*, 1977. Comparison of methods of calibration of a neutron probe by gravimetry or neutron-capture model. *J. Hydrol., 34, 343–356.*

This paper presents a systematic analysis of two methods used for determining calibration curves of neutron probes. The uncertainties resulting from the use of the gravimetric method, with a linear correlation between count rates and water content of soil samples, are considered first, followed by a technique based on the determination of neutron thermal adsorption and diffusion constants. The importance of errors associated with this method is also analysed.

Venn, M.W. and Day, B., 1977. User Manual for the CAPTAIN package. *Inst. Hydrol., Wallingford, Rep. 39.*

Staff of the Institute of Hydrology

J.S.G. McCulloch PhD *Director*
Assisted by Mrs C. Kirby BSc

Analytical hydrology

R.T. Clarke MA *Rainfall-runoff modelling; synthetic hydrology*
J.R. Blackie MSc *Rainfall-runoff modelling; water balance studies*
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Miss E.M. Morris PhD *Rainfall-runoff modelling*
K.J. Bevan PhD *Deterministic distributed models*
K. Blyth DipGeog *Remote sensing techniques*
C.W.O. Eeles *Water balance studies*
R.J. Gurney PhD *Instrument network design; spatial variation*
D.A. Jones PhD *Spatial and time series analysis*
R.J. Moore MSc *Synthetic hydrology; recursive stream-flow forecasting*
G. Roberts PhD *Movement of solutes; hydrological data processing*
Mrs J. Godfrey BSc *Deterministic distributed models*
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F.J. Ayres (Seconded from the Meteorological Office) *Assistant, hydrological data processing*
Mrs A. Matthews *Assistant, hydrological data processing*
Mrs E.A. Snow *Assistant, hydrological data processing*

Physical hydrology

Vegetation/atmosphere interactions

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H.M. Gunston BSc *Agricultural hydrology*
H.R. Oliver PhD *Applied meteorological research*
J.M. Roberts PhD *Physiological controls of evaporation*
J.S. Wallace PhD *Environmental physiology*
I.R. Wright BSc *Interception studies*
N.F. Cowell *Site foreman*

Evaporation flux studies

W.J. Shuttleworth PhD *Eddy correlation research; theoretical micrometeorology*
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Soil hydrology

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M.J. Howard PhD *Unsaturated soil water flux studies*
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Hydrogeology

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C. Neal PhD *Clay mineralogist*
C.J. Smith LRIC *Chemist*
Miss P. Jordan BSc *Environmental engineering*

Applied hydrology

J.V. Sutcliffe PhD *Co-ordinator, commissioned and repayment contracts*

Flow prediction

M.A. Beran BSc *Low flow studies*
A. Gustard BA *Low flow studies*
P.P. Lynn MSc *Statistical models of flood flows*
D.C.W. Marshall MSc *Low flow studies*
Mrs M.J. Stevens MSc *Statistical models of flood flows*
Mrs J.F. French *Assistant*
Mrs A.J. Stratton *Assistant*

Catchment response

M.J. Lowing MSc *Flood estimation techniques*
F.A.K. Farquharson MSc *Variation in catchment response*
C.S. Green PhD *Real-time flow forecasting*
C.H.R. Kidd PhD *Urban hydrology*
J.C. Packman MSc *Urban hydrology*
D.B. Boorman MSc *Variation in catchment response*
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Miss G.A. Price MSc *Urban hydrology*

Water resources

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S.F. Pond BSc *Groundwater*

B.S. Piper MSc *Surface water*
D.S. Biggin *Groundwater*
R.B. Bradford MSc *Groundwater*
J. Bromley PhD *Groundwater*
S.B. Parsons MSc *Surface water*
Miss Y.P. Parks MSc *Surface water*

ODM overseas unit

J.B. Miller PhD *Project co-ordinator*
K.A. Edwards PhD *Kenya hydrology project*
A.N. Mandeville PhD *Water Resources Division, Malawi*
I.G.G. Hogg MSc *Kenya hydrology project*

Computer services

R.F. Templeman PhD *Computer manager*
Miss A. Hill *Operations manager*
A.P.J. Lobley BSc *Programmer*
M.V. Venn BSc *Programmer*
Miss A.J. Beresford-Slinn *Computer operator*
R.G. Barnard *Computer operator*
Miss D.E. Davis *Computer operator*
Mrs G.I. Gordon *Computer operator*
Mrs J. Powis *Computer operator*
Mrs B.E. Culkin *Punchcard operator; tape librarian*

Instruments

I.C. Strangeways BSc *Instrument development*
G.P. Brunsden CEng *Development engineer (digital)*
Mrs M. Turner *Development engineer (digital)*
A.J. Baty *Development engineer (analogue)*
D.J. Harris CEng *Mechanical design engineer*
P.M. Holdsworth *Development engineer (soil moisture measurement)*
P.D.R. Andrews *Workshop manager*
W.S. Insell *Mechanical development engineer*
M.E. Walker *Automatic weather station technician*
R.G. Wyatt *Mechanical design engineer*
C. Fright *Instrument craftsman*

M.R. Stroud *Automatic weather station technician*
M.J. Rutter *Instrument craftsman*
M.T.H. Key *Mechanical design engineer/Safety Officer*
J. Cross *Contract prototype wireman*

Permanent staff at Plynlimon

M.D. Newson PhD *Surface and stream channel characteristics*
J.D.G. Smart BA *Catchment manager*
Mrs A.J. Newson BSc *Flume calibration; spatial variability in rainfall*
J.G. Harrison BSc *Peat hydrology*
J.A. Hudson BSc *Solute transport; snow measurement*
P.J. Hill *Lysimeter studies*
A. Hughes *Network operation; transport manager*

Information services

Mrs C. Kirby BSc *Information officer*
Miss S.B. Neal BA *Librarian*
Mrs P.J. Kisby *Assistant editor, IAHS Bulletin*

Establishment and finance

F.C.S. Adcock *Station secretary/chief finance officer*
S.K. Forbes *Station engineer*
J.B. Comfort BSc *Assistant to finance officer*
J.R. Parker *Personnel administration*
Miss M.P. Saxton *Accounts officer*
Mrs O.M. Andrews *Assistant, personnel administration*
F.W. Freeman *Registry*
Mrs M. Smith *Assistant to accounts officer*
Mrs J.E. Willson *Assistant to accounts officer*
Mrs M.G. Charman *Assistant, personnel administration*
Mrs S.E. Yaxley *Director's secretary*
Miss S.J. Batten *Personal secretary*
Mrs M.E. Hebbert *Audio typist*

Mrs J.V. Patching *Audio typist*
Miss H. Reid *Audio typist*
Mrs L. Siggs *Telephonist*
A.H. Thomas BEM *Transport officer*
R.G. Drewett *Craftsman*
P.J. Kennelly *Driver/handyman*
J.A. Rae *Driver/handyman*
J.H. West *Driver/mechanic*
J.H. Jones *Storekeeper*
C.F.A. Sibley *Caretaker/groundsman*
Mrs B. Karmel *Staff restaurant manageress*

Programme of Research 1978
List of ongoing projects as at 1 April 1978

C = commissioned research
PC = part commissioned
R = repayment work

Research area I — hydrological systems

PC Lumped conceptual models of catchment behaviour
PC Distributed models of catchment behaviour
Time series analysis of multivariable hydrological systems
Network design and spatial variation of hydrological variables
Remote sensing applications
C N-fertilizer applications in upland catchments
C Nutrient studies
Morphometric variables

Research area II — hydrological processes

Development, testing and use of evaporation detection apparatus
Physical controls of evaporation
Biological controls of evaporation
C Interception studies
Fog drip
C Groundwater recharge estimation
Soil physical controls of runoff from first-order basins

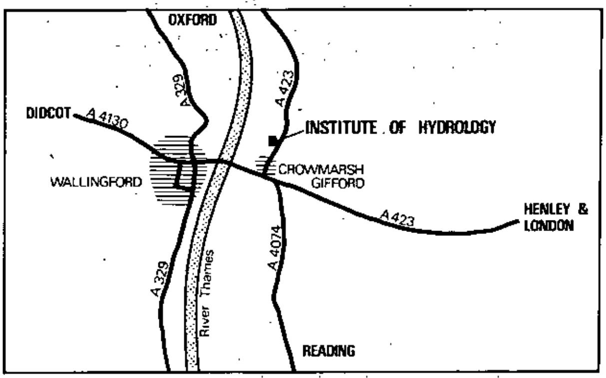
C Nitrogen fluxes in unsaturated chalk
Storm runoff through natural pipes
Shallow groundwater in flood plain deposits
C Urban hydrology
Studies of surface and stream channel characteristics
Runoff from impervious surfaces
Application of dilution gauging to stream runoff studies
Trace element chemistry of natural waters
Alkaline groundwater studies
Hydrochemistry of an estuary

Research area III — applied hydrology

R Water resources of Tehran basin
R Kenya Hydrology Project
R Surface water potential, Botswana
R Short-term advisory studies
R River Dee real-time forecasting system
C Variation in catchment response
C Regional low flow characteristics
C Statistical models for the distribution of flood flows

Instrumentation

Lysimeter studies
Standard neutron probe and autoprobe
Automatic soil station and tensiometers
Automatic weather station for use in climatic extremes
Microprocessors and solid state logging
Low-cost instruments for hydrology



From London

By road

Leave by Cromwell Road, M4 and A423 through Henley towards Oxford to Crowmarsh Gifford. Entrance to the Institute is 200 yards on the left from traffic lights on A423.

By rail

From Paddington to Cholsey and Moulsford (approx 75 minutes) or Didcot (approx 1 hour) then by bus or taxi to the Institute.