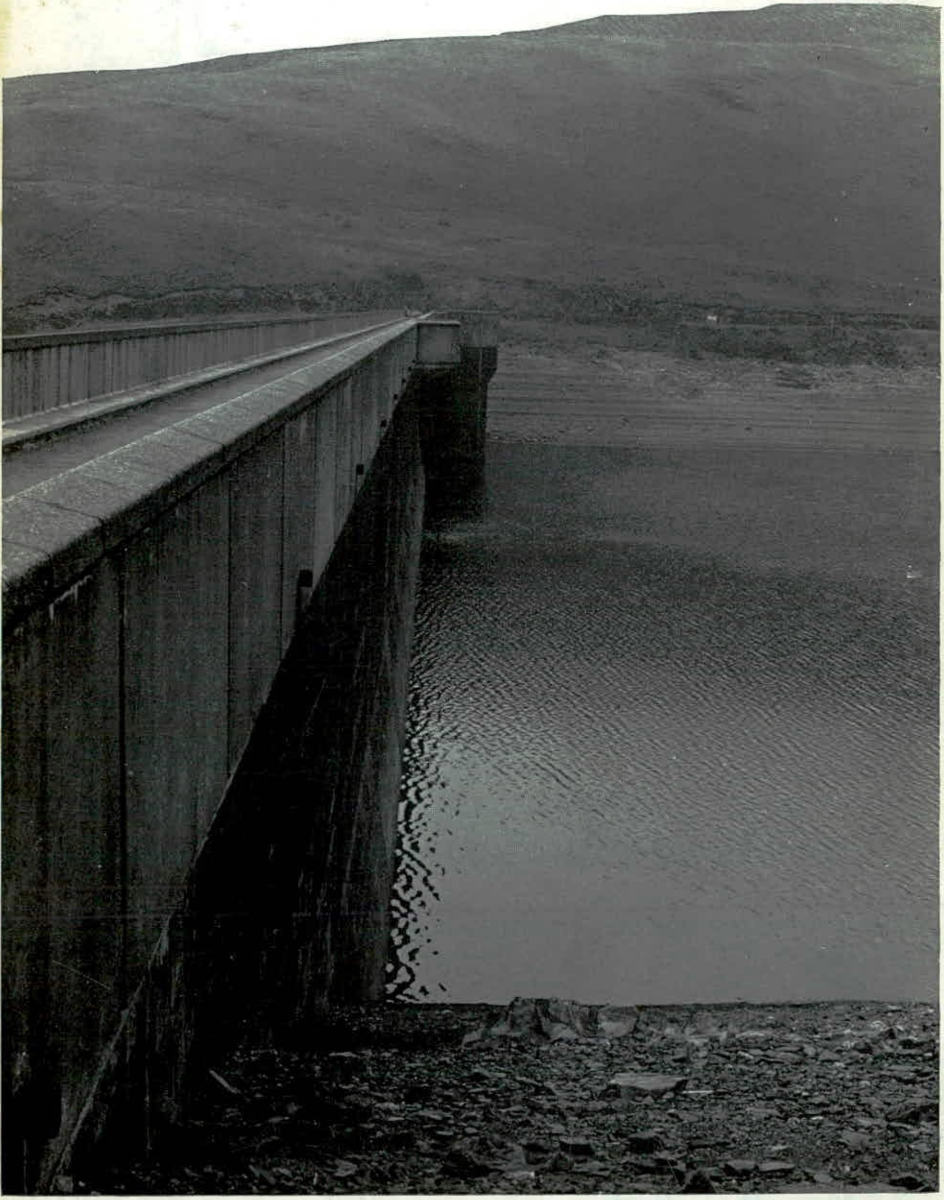
Institute of Hydrology

Research Report 1974-6



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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Natural Environment Research Council

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Contents

Director's Review

Four years ago, in an article entitled 'Hydrology and Government in the UK'* I wrote "hydrology as the science of water would appear to be well placed to adapt to Lord Rothschild's customer-contractor principle" (essentially, "Let those who need the research pay for it"). I continued: "It would therefore be futile to dispute the concept that applied research undertaken by research councils should be funded by the appropriate government department. Of greater relevance is the examination of the NERC's programme for hydrology in the light of Rothschild's definition of contractable R and D projects."

In the event, the Rothschild philosophy was applied with funds transferred in increasing proportions, up to a maximum of about 35% in the financial years, 1973–74, 1974–75, 1975–76. It is with much of this transition period that this report of research is concerned. As predicted, the viability of the Institute of Hydrology has been proven to the extent that in 1975–76, 56% of the annual budget of the Institute is derived from sources outside NERC. Of course, satisfaction of the requirements of customer-oriented research projects has necessitated a substantial reorganisation of the administrative structure of government. Major customers have been required to set up Chief Scientist organisations and series of committees to evaluate research requirements in the first instance, or to make subsequent progress reviews of projects which have been commissioned. From the viewpoint of the Institute which undertakes the work on behalf of the contractor, NERC, substantial effort has been necessary in dividing up a carefully balanced programme into a series of projects for individual financing by the Department of the Environment, by the Ministry of Agriculture, Fisheries and Food, and by the Ministry of Overseas Development. A costing

* McCulloch JSG (1972) *EOS Transactions, American Geophysical Union* 53(7) pp 741–3

system acceptable to the departmental customers has been instituted. Apart from the time of senior staff involved in preparing presentations to senior departmental representatives, submissions for research requirements committees, and reports to research review committees, 2 additional clerical staff in a total complement of 123 have been necessary. It would be less than honest to claim that the imposition of the additional layers of bureaucracy consequent upon the implementation of the Rothschild philosophy have not adversely affected the coherence of the research programme or interrupted the scientific efforts of the staff. Rothschild's ambition of fewer committees and fewer staff in the headquarters of the various research councils has certainly proved illusory; nevertheless, at working level, communications between researchers and staff of executive departments have improved considerably, so that the time lag between the completion of an investigation at the Institute and the application of the results in general practice has been reduced.

This conclusion is well demonstrated by the Flood Study Report,* published in February 1975. This pre-Rothschild project could have been contractable to potential users but was in fact funded directly by the Science Vote, through the NERC grant-in-aid from the Department of Education and Science. Publication was followed by publication of an Institution of Civil Engineers report on Reservoir Flood Standards. It may well be that many consulting engineers are recalculating the hydrological boundary conditions for the reservoirs for which they were responsible in the light of the Flood Studies Report and the new ICE standards. At a two-day Floods Symposium at ICE the various contributions to the report were discussed; further mettings in Edinburgh and Belfast stimulated the interest of the engineering profession and at times led to controversy. The National Water Council has already held two Seminars for potential users both in the water industry and in various consulting organisations. Proposals are well advanced for a much condensed and abbreviated form of the publication to complement rather than substitute for the full report.

* Flood Studies Report. Five volumes. *Published by NERC. at £40.00*

This report of the work of the Institute covers the two financial years, 1974–75 and 1975–76. While it was tempting and would undoubtedly have been easier to make statements of progress on each of the 40 distinct projects which comprise the Institute's programme, the presentation is of an integrated programme with major emphasis on projects which are reaching maturity. One of the major areas of work and of scientific advance is the intensive study of evaporation processes within a forest canopy. These studies have been undertaken in Thetford Forest since 1967 and are now in their final phase; the 1976 summer season is to be the last experimental season at this site. It is timely therefore to review the progress of the experiment and to indicate how the scope and objectives have evolved during the last eight years. The predominant role of interception of rainwater by vegetation has at last been fully evaluated and appreciated. The diversity of published results of comparison of water use of forest versus grassland in different climatic environments can now be interpreted.

Staff of the Institute have been working for many years on an ODM-funded project on the hydrological effects of land use changes in East Africa. The main aim of the project is the analysis of relatively long runs of data from a series of catchment studies initiated in the late 1950s. To this end, more sensitive equipment for the measurement of streamflow, soil moisture and the meteorological variables which control evaporation were installed in 1970–72, alongside the existing equipment, to assist in identifying sources of systematic error. Concurrently with this field work, some 130 catchment years of records of rainfall, streamflow, evaporation and soil moisture have been mounted on computer magnetic tape for quality control and subsequent analysis and mathematical modelling. Two short-term process studies on the water use by tea plantations were initiated in recent years, one using the zero flux plane soil moisture measurement approach and the other an energy balance approach in which sensible heat flux was measured using the 'Fluxatron' equipment as well as net radiation and soil heat flux. The analysis of all the data is now well advanced and publication of the results is expected at the end of 1976.

One measure of the scientific effectiveness of a research organisation is the publications of its staff; those produced by the Institute during the period covered by this report are listed with brief abstracts on pages 87–100. In addition to papers in the scientific journals, there is a series of Institute of Hydrology Reports. This series acts as a particularly useful vehicle for communication of programmes, techniques and analyses often involving considerable amounts of data, in greater detail than would be practical in periodicals. A new venture in such dissemination of information has been the issue of a national catalogue of all known recording raingauges prepared in conjunction with the Meteorological Office and Dr P Kelway of Birmingham University (now with the Northumbrian Water Authority). This computerised list gives information on location, operating authority, dates of operation, microfilm and data availability. With the co-operation of all who operate such gauges, we shall be able to keep the master catalogue fully up to date and be able to bring out revised editions as required.

J S G McCulloch
Director

Hydrological Systems

Work at the Institute on hydrological systems falls under three headings:

a the development of rainfall/runoff models for test using data collected from the Institute's research catchments and others;

b the development of statistical and operational research methods for

(i) estimating the frequencies of extreme hydrological events by Monte Carlo simulation ('synthetic streamflow generation') and

(ii) assessing the adequacy of instrument networks providing mean areal estimates;

c the management of catchment studies in order to provide data for research purposes on precipitation, soil moisture, meteorological variables and streamflow.

The Hydrological Systems group therefore occupies an intermediate position between the Process Studies group on the one hand, and the Applied Hydrology group on the other: the Institute's studies of hydrological processes investigate in detail the physical principles by which water changes phase and position in its course from precipitation to runoff, and the work of the Systems group is to integrate process study results into a unified mathematical-physical description of river basin behaviour (or 'model') for use by the Applied Hydrology group and others. Furthermore, because rainfall-runoff models serve a number of different purposes ranging from filling in gaps in a streamflow record to predicting the likely effect on a streamflow regime of a change in land use, a range of models is required depending upon the type, quality and quantity of data available for estimating whatever constants they contain, so that this range may include both the crudely empirical and the physically sophisticated.

The development of rainfall-runoff models

Lumped catchment models

In one type of river basin model called, somewhat unhappily, 'lumped', the relation describing streamflow (output) in terms of precipitation and meteorological variables (input) takes no account of any spatial variability in the latter, or in the processes by which precipitation is converted to streamflow. The lumped conceptual model of basin behaviour developed at the Institute has been described at length in earlier reports, and it is sufficient here to say that the basin is assumed to function as a vertical stack of reservoirs with simple rules governing the transfer of water from one to the next, or back to the atmosphere as evaporation. Given a continuous streamflow record and a contemporaneous record of precipitation and of meteorological data combined to give Penman's estimate of open water evaporation, E_0, the constants in the model are estimated by least squares: that is, using a curve-fitting procedure, albeit one for which the curve bears some resemblance to the physical reality. Such models are highly suitable for filling gaps in streamflow records and for short-term streamflow forecasting; however, their application is critically dependent upon the existence of a gauging structure in the basin, and if none is present, alternative estimates of the model parameters using, for example, multiple linear regressions on catchment characteristics, may have very low precision.

Whilst a streamflow record (basin output) is therefore highly desirable for the calibration of a lumped model, situations arise (and may be expected to become more frequent) where there is more than one output variable. On the Institute's research catchments for example, soil moisture change ΔS is measured in addition to precipitation P, streamflow Q, and the meteorological variables from which E_0 is calculated, and ΔS may be regarded as an output variable in the sense that it is dependent upon precipitation input and atmospheric evaporative demand. Similarly, on the Severn catchment, throughfall and stemflow are measured at selected sites, and may be regarded as dependent upon P and E_0; other cases arise also where additional dependent variables describe the quality of runoff water or its sediment content. Expressed formally, the usual type of conceptual model postulates a relation between Q_t (the total streamflow in the time interval $(t-1, t)$), P_t, $E_{0,t}$ (the precipitation and open-water evaporation in the same interval) and parameters θ of the form

$$Q_t = f(P_t, P_{t-1}, \ldots; E_{0,t}, E_{0,t-1}, \ldots; \theta) + \varepsilon_t$$

where the function $f(.)$ is usually too complicated to be written down in an analytical way, and rules for its calculation are expressed as a computer flowchart; the residual ε_t measures lack of fit. Where soil moisture change $\triangle S_t$ is also measured and regarded as a second dependent variable, a similar expression may be written:

$$\triangle S_t = g(P_t, P_{t-1}, \ldots; E_{0,t}, E_{0,t-1}, \ldots; \theta) + \eta_t$$

where the parameter sets θ in the two expressions are either identical or have most elements in common.

Using this more general model, a project has been undertaken which had as one objective a study of the usefulness of available soil moisture records for assisting with model calibration (that is, estimation of the θ). Incorporation of soil moisture data in the model calibration procedure was achieved by generalizing the commonly-used least-squares criteria to a likelihood function, a generalization made at the expense of introducing further assumptions regarding the probability distribution of model residuals. Streamflow, soil moisture, precipitation and evaporation sequences were used from two experimental catchments: the Cam above Dernford Mill, and the Ray at Grendon Underwood.

The goodness of model fit was measured using the commonly-used quantity E defined by

$$E = 100(F_0^2 - F_1^2)/F_0^2$$

where F_0^2 is the sum of squared deviations of the streamflow observations calculated about their arithmetic mean, and F_1^2 is the sum of squared deviations of the observed streamflow values from those given by the model. The efficiency E has an upper limit of

100% when each observed streamflow value is exactly equal to the fitted value given by the model; the poorer the model fit, the greater the departure of E from 100%. Its value was calculated for both the streamflow sequence (E_q) and also for the soil moisture sequence (E_s); moreover, these values were calculated for the cases (a) where the model calibration used only the streamflow data; (b) where it also used the soil moisture data. Furthermore, since the real test of a model is its usefulness for prediction, E_q and E_s were calculated using data from a prediction period which had not been used to assist the model calibration. Table 1 shows the values obtained for E_q and E_s calculated for both the Cam and Ray data sequences; columns headed C1, R1 show the values of E_q, E_s where model calibration used only the streamflow data, and those headed C2, R2 show the values of E_q, E_s where soil moisture data were also used. The columns headed C3, R3 show E_q, E_s where

Table 1. *Efficiencies of models fitted (i) using streamflow record alone (columns C1, R1); (ii) using both streamflow and soil moisture records (columns C2, R2, C3, R3).*

(i) Calibration period

	C1	C2	C3
E_q:	77·5	77·5	74·3
E_s:	68·5	70·3	80·5

Calibration period: January 1968–December 1969; 6 hourly records.

	R1	R2	R3
E_q:	96·2	96·1	95·8
E_s:	91·9	90·3	91·4

Calibration period: May 1970–August 1971; 3 hourly records.

(ii) Prediction period

	C1	C2	C3
E_q:	61·4	61·4	47·6
E_s:	78·4	80·5	77·4

Prediction period: January 1970–December 1971; 6 hourly record.

	R1	R2	R3
E_q:	75·9	75·6	75·5
E_s:	73·1	68·3	76·5

Prediction period: September 1971–December 1972; 3 hourly records.

streamflow, precipitation and E_0 were accumulated over the intervals defined by the dates on which soil moisture was measured. (In columns C3, R3, therefore, there were equal, but small, numbers of observations on all variables; in columns C1, R1, C2, R2 precipitation, streamflow and E_0 observations were far more frequent than those of soil moisture).

Table 1 shows that for the Ray catchment the model efficiency as measured by both E_q and E_s is not greatly affected by the inclusion of soil moisture data either in the calibration or prediction periods. Results from the Cam catchment tend to be conflicting, since inclusion of soil moisture data is associated with a considerable increase in E_s during the calibration period but a considerable reduction in E_q during the prediction period. Some decrease in efficiency was not unexpected for certain cases, since the calculation performed for Table 1 is analogous to that where an improvement in precision is sought for estimates of parameters describing a probability distribution of annual maximum discharge by correlating these annual maxima with others in a longer record at a nearby gauging station. If the correlation between the two sequences is small, the estimates obtained from the combined use of the two series may have poorer precision than those obtained using data in the shorter sequence alone. This 'dilution of information' may also be expected to occur in some cases where information in a soil moisture sequence is used in estimating model parameters in the streamflow model. Judged by Table 1 therefore, the frequency of soil moisture measurement and its degree of spatial replication was not sufficient to convey significant improvement in precision of model parameters, or in model efficiency; nevertheless, the technique may have value where soil moisture can be measured more frequently and at more sites, possibly by automatic means. Figures 1 and 2 show measured and calculated soil moisture values for the Cam and Ray catchments respectively; values for both the calibration and prediction period are shown. A full account of the study has been published (J R Douglas, R T Clarke and S G Newton: The use of likelihood functions to fit conceptual models with more than one dependent variable. *Journal of Hydrology* 29 (1976) p. 181–198).

A further application of the likelihood function was considered in which null hypotheses were tested concerning the equality of model parameters in the Plynlimon paired catchment study. Using a 13-parameter model for each of the two major catchments (the Wye catchment under pasture, and the Severn catchment largely under forest), likelihood-ratio tests were used to test hypotheses that the parameters controlling each process in the model were identical for the two catchments. Statistical analysis showed that whilst every model parameter for the Severn differed significantly from its corresponding value for the Wye—a result not unexpected in view of the large volume of data used, 3664 3-hourly totals of precipitation,

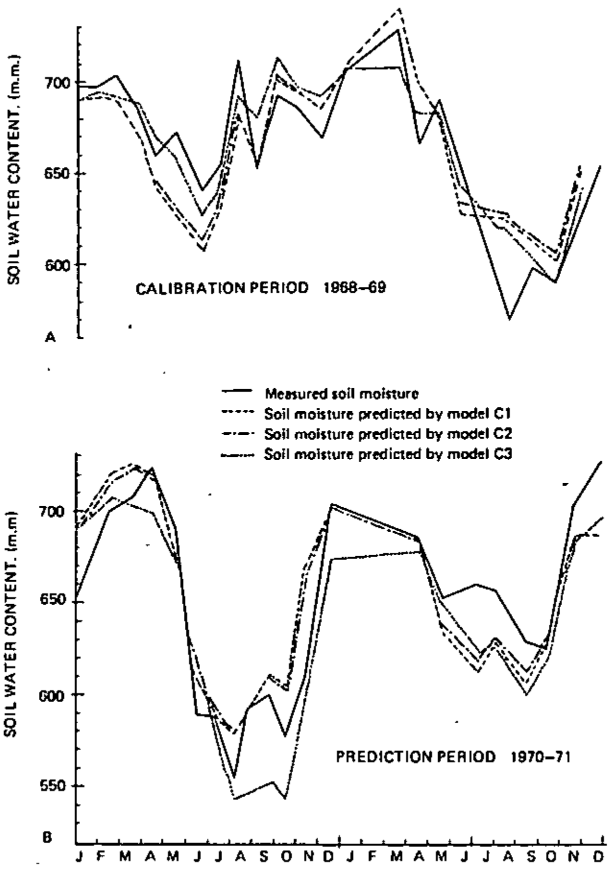


Figure 1. *A. Observed and fitted soil moisture, Cam catchment: 1968–69 B. Observed and predicted soil moisture, Cam catchment: 1970–71*

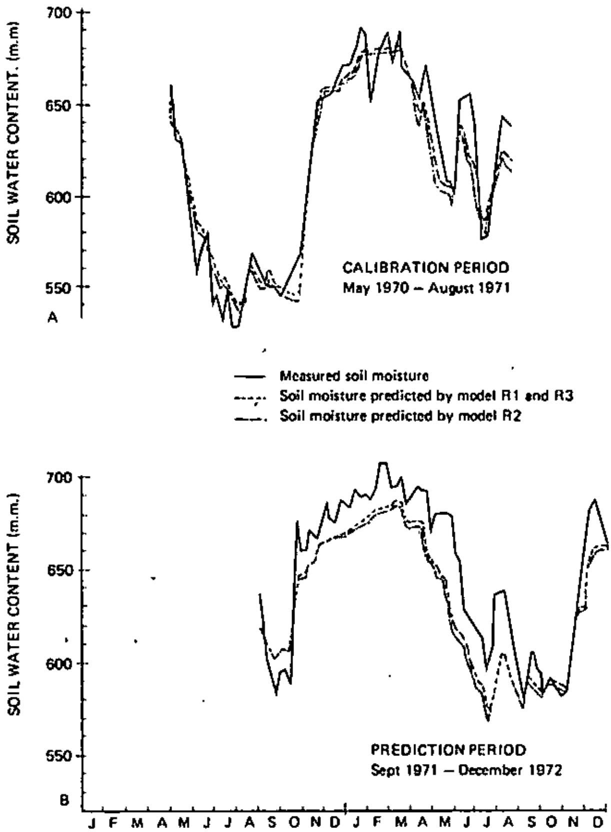


Figure 2. *A. Observed and fitted soil moisture. Ray catchment, May 1970–August 1971*
B. Observed and predicted soil moisture, Ray catchment, September 1971–December 1972

streamflow and E_0, for each of the Wye and Severn catchments—the largest differences were found between parameters governing the interception process, and the smallest differences between parameters governing the routing of runoff to the catchment outfall. This supports the results of other investigations suggesting that interception losses may well constitute the major difference in the hydrological behaviour of the two catchments. A full account is given in the paper referred to above.

Distributed catchment models

The conceptual modelling methods described in the last section require extensive sequences of precipitation, streamflow and meteorological data. These are available for the densely instrumented catchments at

Plynlimon; in the future, however, it is likely that the Institute will be required to extrapolate results from Plynlimon to basins with little or no instrumentation, and to answer questions concerning the effects on the time distribution, quantity and quality of runoff, of different vegetative types on basins with topography and geology very different from those at Plynlimon.

In the absence of good hydrological records for such a basin, one approach is to describe its behaviour in terms of physically-based differential equations governing the movement of water through the soil and over the basin surface; these will also include parameters to be given numerical values, some of which, it is hoped, can be estimated from inexpensive field measurements in whatever basin is under study.

A model is therefore being developed for which the Wye and Severn catchments have been divided into about 25 areas, represented by 'slope elements' or 'channel elements'. A slope element, representing part of a hillside, consists of a layer of soil of constant thickness and homogeneous properties resting upon an inclined impermeable stratum. The area and inclination of a slope element (which is rectangular) are arranged to be equal to the area and average slope of the hillside it represents. Channel elements represent sections of the major streams and are straight with rectangular cross-sections. The length of a channel element is the shortest distance between the upstream and downstream boundaries of the corresponding stream section, and its width the average width of the stream. The outflow from one element may be used as inflow to another; thus the output hydrograph may be calculated for each element in turn, and the last (channel) element gives the catchment hydrograph.

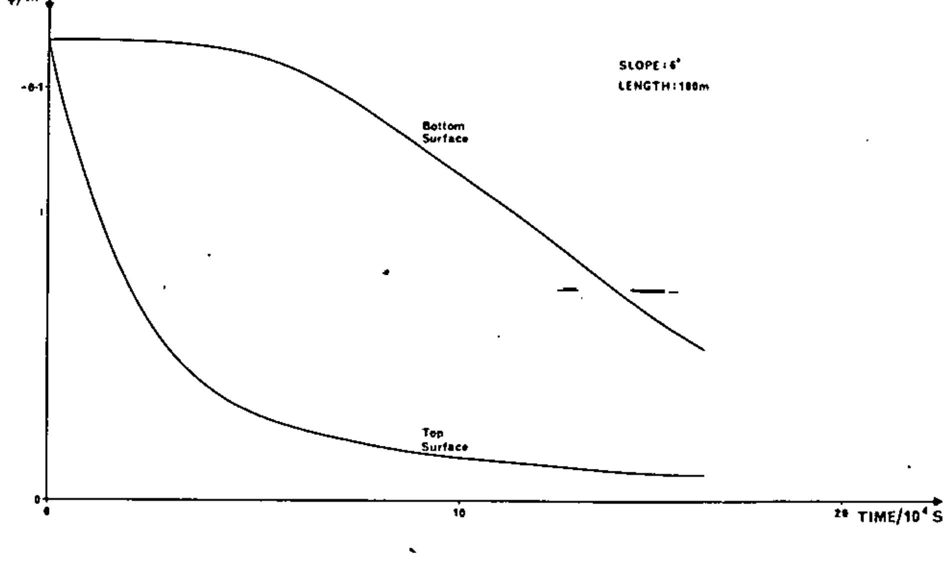
It has been assumed that infiltration and throughflow may be adequately described by the equation for flow in a non-swelling porous medium

$$C\frac{\partial\psi}{\partial t} = \nabla.(K\nabla\psi) + \frac{\partial K}{\partial z}$$

where ψ is the hydrostatic pressure potential, $K(\psi)$ is the capillary conductivity, and C the specific moisture capacity; z is the vertical co-ordinate. Hysteresis in the relation for $K(\psi)$ is ignored because the emphasis is on the soil's response to heavy storm rainfall, and hence on the wetting limb of the hysteretic loop only. The equation is solved for two-dimensional flow in the sloping soil layer, or slope element, for which the vertical cross-section down the slope is given as a parallelogram with two vertical edges: the lowermost vertical edge is the stream bank, whilst the uppermost is either at the catchment boundary or at the junction with another idealized soil layer with different surface slope. The flow equation is transformed by the Kirchoff transformation, and is then solved by an implicit finite-difference scheme; this part of the model has now been tested for various extreme conditions which will not necessarily arise when it is used to predict runoff from the Plynlimon catchments, since the aim has been to establish a wide range of conditions for which the finite-difference scheme is known to be stable.

Figure 3 shows the increase in hydrostatic pressure potential ψ at the top and bottom surfaces of a gently sloping soil layer 50 cm thick as rain falls on dry soil; Figure 4 shows the decrease in ψ as water wells out of a saturated soil, the adjustment to ψ being most rapid at the soil surface, as expected. The curves are smooth, and the finite difference scheme used does not give

Figure 3. *Increase in hydrostatic pressure potential at top and bottom surfaces of a gently sloping soil layer*



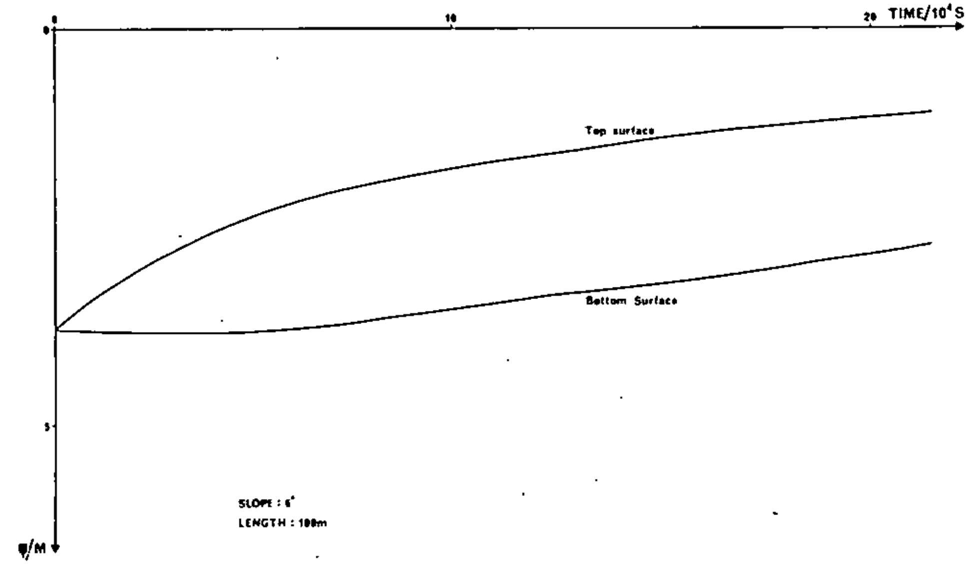


Figure 4. *Decrease in hydrostatic pressure potential as water leaves saturated soil*

rise to any significant fluctuation of ψ with time in any case so far tested. Flow at the bottom of the slope, or indeed at any position in the soil, can be calculated from the distribution of ψ, and the results for steep slopes are similarly stable.

The complex network of rivulets and shallow soil pipes by which surface runoff enters the main channels of the Wye (and, in the case of the Severn catchment, the parallel ditch system superimposed on the basin when the trees were planted) are idealized to a shallow-water flow process described by the St. Venant equations, given by a continuity equation together with the momentum equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial h}{\partial x}\cos\theta = g(\sin\theta - S_f) - q\frac{(u-u_r)}{h}$$

where u, h are water velocity and depth at distance x along the soil surface, then $\theta = S_0$ is the slope of the surface, u_r is the x-component of the precipitation velocity, and q is the rate of precipitation input at the surface per unit width of surface slope; and S_f is the friction slope, described by the Chezy relation. After much difficulty in finding stable solutions for these equations using the low Chezy numbers given in the literature as typical of grassed surfaces, a program has now been developed that is stable for low Chezy numbers. The same program can be used to describe flow along the stream channels.

To apply this distributed model to an ungauged catchment, the following data must be supplied:

a the geometry of the slope and channel elements;

b a soil moisture characteristic curve relating ψ to θ, the moisture volume fraction of the soil, and a curve relating the hydraulic conductivity $K(\psi)$ to ψ;

c empirical parameters for the Chezy expression for the friction slope S_f used in solving the shallow-water equations.

Whilst the model works well for the simple catchment geometries considered so far, considerable development is required before it will be capable of predicting the hydrograph from a configuration as complex as that containing the twenty-five or so planes into which the Wye and Severn basins have been divided, although no new principle is involved.

A second model is also being developed for the Plynlimon catchments in which each is divided into elements of four types: peat hag areas, grassy slopes, riverine marsh areas, and streams. Field measurement is yielding a relation between discharge from each type element and the depth of water it contains, and catchment behaviour is characterized by these relations, the areas covered by the different element types, and their spatial orientation. This approach is still in its early stages.

Statistical methods for forecasting, and frequency studies

Time series analysis of multivariate hydrological systems

Records of precipitation, soil moisture and streamflow and more generally, of water quality and sediment transport variables, may be regarded as time series (sequences of observations in a particular time order), and the relationships between them described in statistical terms. Such purely statistical descriptions have application (i) where it is necessary to forecast, in real time, the behaviour of the system at some time-interval ahead, as where water quality variables at a downstream station must be forecast from those upstream; (ii) where the frequency (F) of some hydrological event (such as the failure of a reservoir to meet the water demand made on it) is to be estimated by using the statistical description to generate synthetic sequences—of streamflow, for example—derived from computer-generated sets of pseudo-random numbers.

For the forecasting application (i), an interactive graphic package has been developed for identifying the statistical model suitable for describing the relation between one input variable (such as streamflow at an upstream station) and one output variable (streamflow at a downstream station). This package uses programs originally developed by the Department of Control Engineering at Cambridge University. Once the statistical model has been identified, its parameters are estimated using a recurrence least-squares algorithm which facilitates study of the extent to which model parameters are time-variant. A multivariable extension of the estimation algorithms has been coded in FORTRAN, and is being tested using hydrological data; the relevant package will have wide application for forecasting and simulation of water quantity and quality variables for both control and design problems.

For the simulation application (ii), studies have been made of the usefulness of efficient Monte Carlo simulation methods for improving the precision of the estimated quantity F. Such methods have been widely used in industry and the physical sciences, but appear from the literature to have had at most a limited use in hydrological simulation. In the preliminary studies made so far, considerable increases in precision may result from the use of control variates (by which a simulation problem is simplified to one that can be solved analytically, and the analytical solution used to assist in solving the problem of interest) and by the use of antithetic variates (by which two negatively-correlated estimates of F are sought, such that the mean of the two estimates has variance smaller than that of either estimate separately). Both methods show considerable promise and further development will determine whether the promise is fulfilled when they are applied to large-scale hydrological simulation problems.

The adequacy of instrument networks

Because hydrological variables (such as precipitation, soil moisture change, E_0) vary spatially as well as in time, work is in progress at the Institute which has as its objective the statistical description of spatial variation with a view to (a) deriving improved measures of the reliability of mean areal values; (b) deriving improved interpolated estimates at sites where a variable is not measured in the field. In the initial work, monthly precipitation from the ground-level storage gauge network at Plynlimon was studied, and analysis of variance used to distinguish the effects of altitude, aspect and slope of site on gauge catch. The technique was also used to compare the catches of ground-level gauges in the unforested parts of the Severn catchment with those of gauges mounted on masts above the forest canopy using the statistical model

$$y_{ijk} = \mu + a_i + l_j + \varepsilon_{ijk}$$

where μ is the areal mean; a_i is an altitude effect associated with all gauges in altitude in class i; l_j is the effect of gauge 'level' (ground level versus canopy level) and ε_{ijk} is the random error in the observed gauge catch y_{ijk}. A full account has been published recently (Newson and Clarke, 1976).

Table 2 shows the values of the 'level' constants l_1, l_2 (free from altitude effects) obtained month by month for the period April 1971–March 1973, together with the arithmetic mean for all 18 gauges. In 13 of the 24 months, ground-level gauges caught more than the overall mean (since the values of l_1 were positive in 13 months of the 24); in the remaining 11 months they caught less. On average, over all 24 months, ground-level gauges caught 2·8 mm more than the monthly mean (174·4 mm) and the canopy-level gauges caught 1·8 mm less ($7\times2{\cdot}8+11\times-1{\cdot}8 = 0$, apart from rounding error). Because no test for the significance of the altitude effects is possible using the analysis at present under discussion, the altitude constants a_A, a_B, a_C, a_D are not set out in Table 2. This table also shows that significant ($P < 0{\cdot}05$) departures from zero of the level constants, l_1 and l_2, occurred in only 3 months of the 24 (February and March 1972, February 1973). All three were months when snow fell at Moel Cynnedd, (also known as

Table 2. *Paramaters l_1, l_2 representing the difference between ground-level and canopy-level gauge catch, April 1971–March 1973*

	Mean, all gauges	Ground level (l_2) *millimetres*	Canopy level (l_1) *millimetres*	Snow days, Moel Cynnedd†
Apr. 1971	71·2	+0·8	−0·5	0
May 1971	75·2	+2·1	−1·3	0
June 1971	192·4	+2·4	−1·6	0
July 1971	71·1	+1·2	−0·6	0
Aug. 1971	217·8	−1·3	+0·8	0
Sept. 1971	89·7	+1·5	−1·0	0
Oct. 1971	211·2	+6·9	−4·4	0
Nov. 1971	3·079	+8·9	−5·7	7
Dec. 1971	127·9	−0·6	+0·4	3
Jan. 1972	227·6	+10·1	−6·4	8
Feb. 1972	145·9	+18·6*	−11·8*	6
Mar. 1972	213·2	+21·1*	−13·4*	3
Apr. 1972	301·2	+18·8	−12·0	0
May 1972	145·8	−6·5	+4·1	0
June 1972	198·1	−15·9	+10·1	0
July 1972	141·0	−6·4	+4·1	0
Aug. 1972	123·8	−5·0	+3·2	0
Sept. 1972	62·0	−2·4	+1·5	0
Oct. 1972	81·1	−1·6	+1·0	0
Nov. 1972	328·5	−3·5	+2·2	1
Dec. 1972	254·8	−5·5	+3·5	1
Jan. 1973	176·4	+5·7	−3·6	4
Feb. 1973	283·4	+26·7*	−17·0*	9
Mar. 1973	138·6	−8·4	+5·4	1
Overall mean	174·4	+2·8	−1·8	
Mean, months when snow fell	220·4(10)	+7·3	−4·6	
Mean, months when no snow fell	141·5(14)	−0·4	+0·2	

* Denotes statistical significance ($P < 0{\cdot}05$).

† National Grid Reference SN 843877.

Tanllwyth), a daily meteorological station in the Severn catchment: Table 2 shows the number of days on which snow fell there. If means are taken over all months when snow fell, gauges at ground level caught 7·3 mm more precipitation over a month than the mean for all gauges and those at canopy level about 4·6 mm less (Table 2). Differences between ground-level and canopy-level gauges were much less evident in snow-free months when, on average, ground-level gauges caught about 0·4 mm less and canopy-level gauges about 0·2 mm more, than the mean for all gauges.

The management of catchment studies

The Plynlimon catchments

Precipitation measurement

The original network of 39 monthly storage gauges, sited in the Wye and Severn catchments according to a domain theory designed to sample various combinations of aspect, altitude and slope (see IH Report No. 27), has continued to function together with the six Dines recording gauges, three in each catchment. To provide a check on the adequacy of the network, a replicated network of Rimco tipping-bucket gauges, coupled to event-recorders, was sited in the Cyff subcatchment for a six-month period; preliminary analysis (paired comparison *t*-tests) of the monthly catches by the replicate network indicates satisfactory agreement between mean areal rainfall calculated for the two networks. A similar replicated network has been sited by domain theory in the Hafren subcatchment, but the data from it have yet to be analysed. The full record from the replicated networks (giving 5-minute catches by the Rimco gauges) is also valuable for testing the distributed models of catchment behaviour by which predictions can be made of the effects of afforestation in other high rainfall areas.

Because of cost and the relative infrequency of snowfall at Plynlimon, the proposal to measure snowfall using snow pillows has been abandoned; instead,

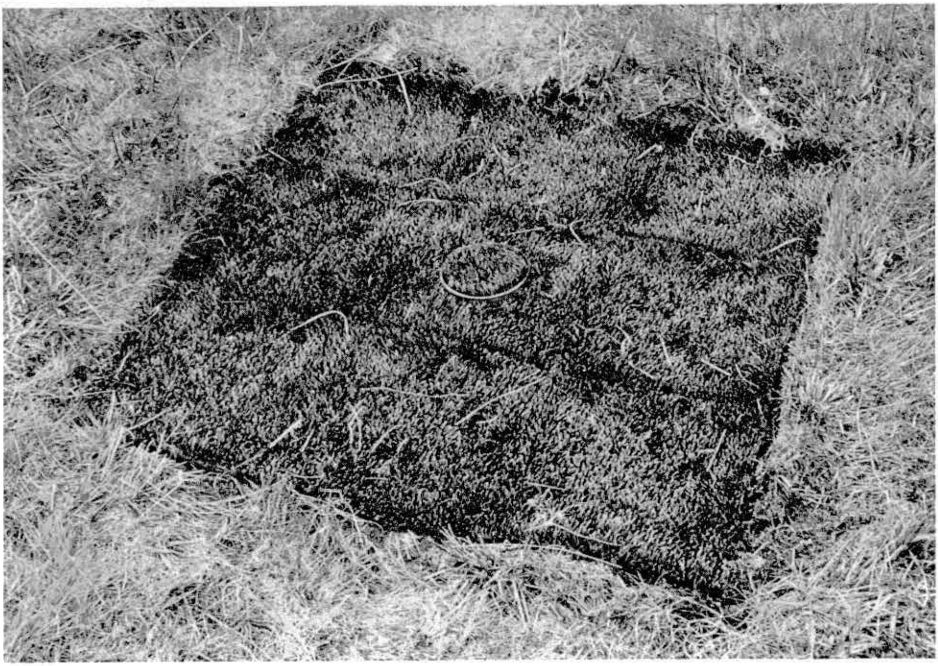


Figure 5. *Raingauge covered by artificial grass for snow measurement*

ground-level Rimco gauges covered with synthetic turf have been installed at four sites within the catchment (see Figure 5). These record on data-loggers the input of water as snowmelt at those sites where snow depth is measured by terrestrial photogrammetry and where water equivalent is measured by snow courses. So far, no significant snowfalls have occurred.

Soil moisture network

The original network of 59 neutron access tubes consisted basically of six lines of tubes perpendicular to the contours; these were read at approximately monthly intervals (sometimes more frequently in summer, when soil moisture content is relatively low, and less frequently in winter, when Plynlimon soils are usually saturated). Additional tubes in the catchment were read less frequently, depending upon the severity of weather conditions. An analysis of variance, by which the total variation in soil moisture $\triangle S$ for each catchment was divided into components, suggested that differences between mean values of $\triangle S$ calculated from the six lines were seldom greater than would be expected from chance variation; the six lines of access tubes were therefore reduced to three, one in the Severn catchment (Hore sub-catchment) and two in the Wye (Cyff and Nant Iago sub-catchments). These three lines now provide estimates of the mean soil moisture change $\triangle S$ within each main catchment.

Meteorological network

Meteorological variables for the calculation of Penman's potential evaporation, E_T, continues to be recorded at the station at Moel Cynnedd which is visited daily. The four pairs of automatic weather stations continue to operate and have been augmented by one additional pair sited above the forest canopy on steel towers at the interception site just outside the Severn catchment; previously, all automatic weather stations in the Severn had been mounted at ground level either in the clearing at Moel Cynnedd

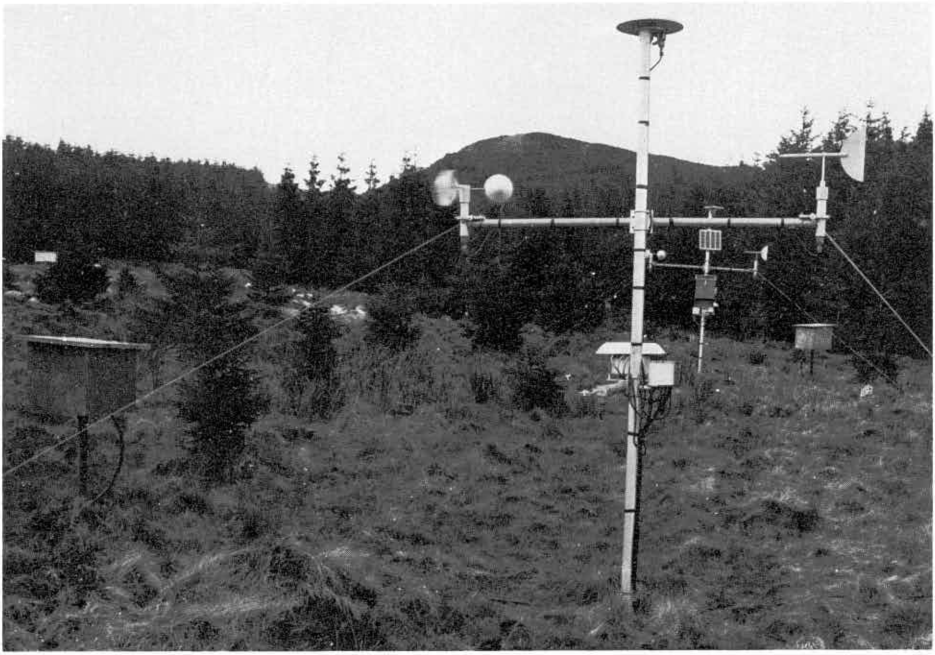


Figure 6. *Automatic weather station with solar panel*

or above the tree line at Carreg Wen. One of the stations at Moel Cynnedd has operated successfully on solar power since April 1975 (see Figure 6).

For the early years of the Plynlimon study, no net radiometer was sited within either catchment. In the absence of measurements of net radiation, it had to be estimated using measurements of solar radiation at the Dolydd office, estimates of net long-wave radiation, and an assumed albedo. The albedo values used were 0·25 for the hill pasture of the Wye, and 0·15 for the coniferous forest of the Severn. In 1974 and 1975, both incident and reflected short-wave radiation were measured to calculate the albedo as a check on the assumed values. For the Wye, 28 sites selected according to the 'domain theory' (see IH Report No. 27) in May 1974 gave an areal mean albedo of $0{\cdot}20 \pm 0{\cdot}004$; a similar programme in June 1975, using 34 sites, gave a mean albedo of $0{\cdot}19 \pm 0{\cdot}004$. Despite the small standard errors, considerable spatial variation was found between individual albedo measurements; yet no significant variation could be accounted for in terms of differences in altitude, slope and aspect. For the Severn catchment, albedo over the canopy was recorded by mounting the radiometers on a steel tower at one site only; the mean albedo for a five-day period was $0{\cdot}11 \pm 0{\cdot}002$.

River level gauging

The gauging structures continue to present problems. Some erosion has resulted from the heavy sediment loads transported through them in times of flood; furthermore, the sediment is sometimes deposited as shoals immediately downstream of the structures, and continual vigilance is necessary to ensure that such shoals are dispersed as soon as they appear. If allowed to remain, they would cause ponding that would distort the measurement of water-level in the stilling-wells of the structures. The concrete in the Severn trapezoidal flume has eroded severely and in May 1975 the flume invert was rebuilt using metal tiles. An intensive programme has been undertaken to verify the theoretical calibration curves by dilution gauging and current metering, the latter with guidance from the Hydraulics Research Station; Braystoke current meters mounted on a vertical rod lowered from a portable aluminium bridge spanning the structure were used to take readings at a minimum of twelve positions across the Severn trapezoidal flume (see Figure 7).

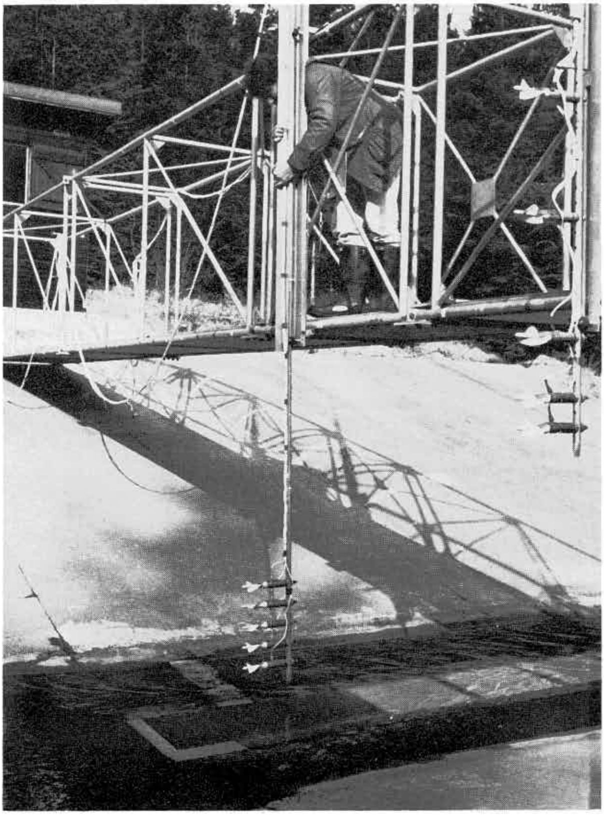


Figure 7. *Current metering at Severn flume*

Except for the Hafren flume, where difficulties have been experienced with the Leupold-Stevens recorder, all Fischer-Porter gauges have now been removed; they have been replaced by the Institute's own water-level magnetic tape loggers. Leupold-Stevens recorders continue to be used (except for the Hafren) to provide a back-up facility should the Institute recorders fail to work properly; the visual display of river stage plotted against time is of great value as a field check and where a storm hydrograph is to be examined shortly after its occurrence.

Other research catchments in the United Kingdom

Because of other commitments, data from the Institute's research catchments on the Ray at Grendon Underwood and on Coal Burn, a tributary of the Irthing, have received little attention. For the Ray catchment, a visiting worker, Dr Ian Simmers from Waikato University, New Zealand, has used soil heat flux data to assess the possible error to the Penman estimate from ignoring soil heat flux when calculating the energy term; his preliminary results suggest that the correction is negligible and unlikely to account for the seasonal discrepancies between actual evaporation and E_T that have been noted even when soil moisture is not limiting.

In preparation for the application of the distributed model (described earlier in this report) to both the Ray and Coal Burn catchments, the topography of each has been simplified into a series of slope elements and channel elements. On the Ray, a study is beginning to determine how far field drainage may have affected the runoff hydrograph during the period of record; modelling of the rainfall-runoff relation on Coal Burn will have the same objective as on the Plynlimon catchments, namely, description of the land-use change.

Land use changes in Kenya

Catchment studies

Sponsored by ODM, several staff from the Institute have been based in Kenya for some years, running a joint project with the East African Agricultural and Forestry Research Organisation and Kenyan Government departments on the hydrological effects of land use change from montane rain forest to tea estate and from bamboo to pine plantation or sheep pasture. Initial analyses of the many years of data using energy and water balance approaches and the application of conceptual modelling techniques showed a variety

Figure 8. *90° V-notch weir in the bamboo forested catchment at Kimakia, Kenya*

of systematic errors, which were unacceptably high in relation to the differences between catchments. Consequently, considerable effort has been devoted to detecting, quantifying and correcting as many as possible of these errors, using the data from more sensitive equipment installed in recent years.

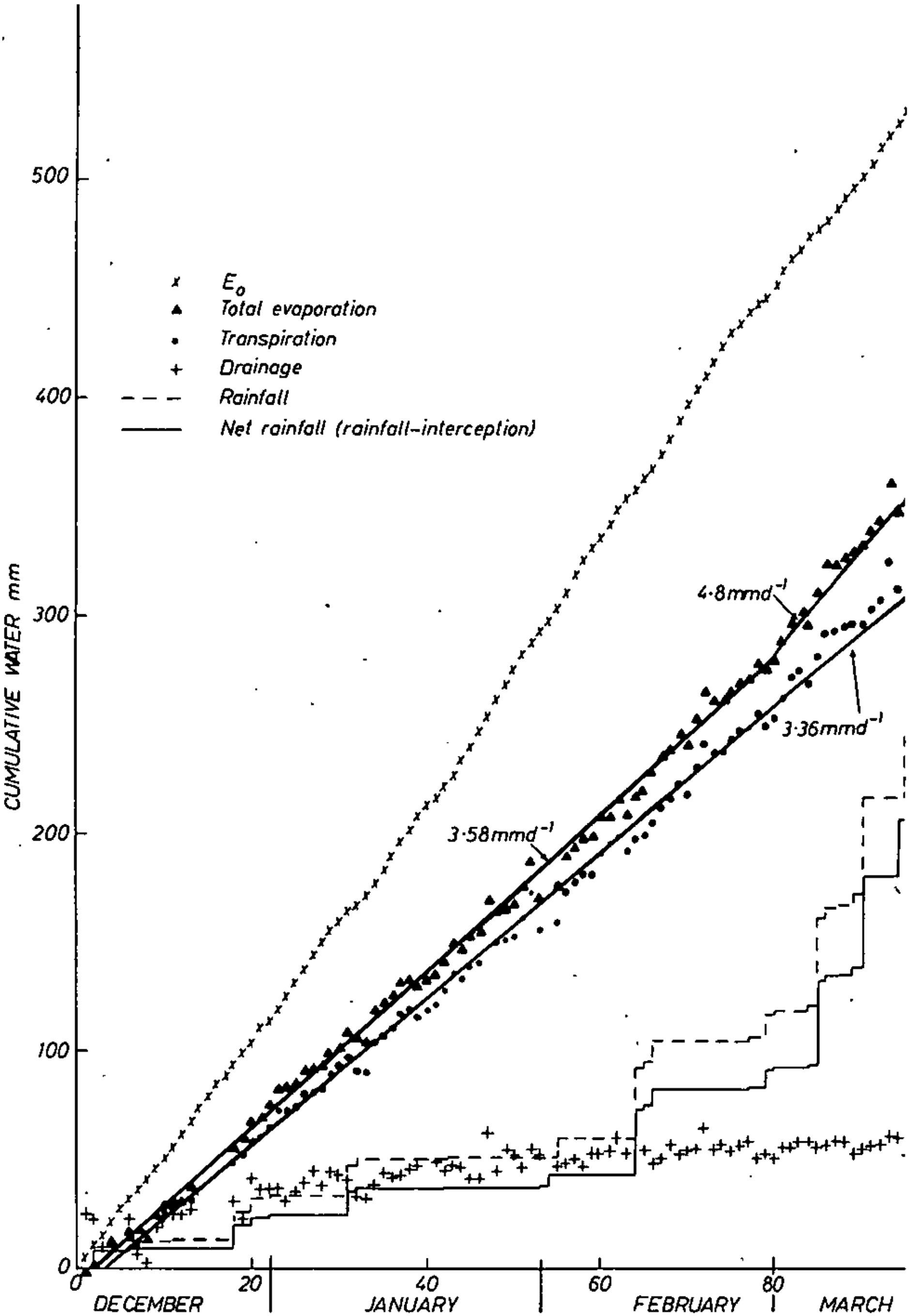
This exercise highlights the difficulties involved in experimental catchment studies. The quality of the data must be very high indeed before any confidence can be placed in the magnitude of differences determined between catchments. Any systematic errors in the individual terms are compounded in a water balance analysis. In fitting models to the data such systematic errors present will be inevitably integrated into the model parameter values. If the models are to be used operationally on the same catchments the forecast data will be of comparable accuracy to the historic record; if, however, the models are to be used on other catchments the in-built systematic errors will be combined with any present in the input data and can result in totally misleading predictions.

Soil moisture data

Monthly gravimetric profiles from three sites in each of four catchments are available for the period 1958–72, together with neutron probe readings from more intensive profile networks in these catchments, plus one other, at monthly or ten-daily intervals from 1968–74. After re-checking the calibrations using additional data, neutron and gravimetric catchment soil moisture determinations were compared for the overlapping period 1968–72. Since sampling dates, frequencies and densities differed between the two methods, a harmonic model, with coefficients determined by linear multiple regression, was fitted to each set of data; the same method was also used to compare the variations in soil moisture content in adjacent catchments and under differing vegetative types within catchments.

In addition, short-term water use, over periods where percolation beyond the sampled profile depths could be considered negligible, was obtained from soil moisture data. Despite the scatter, these figures

Figure 9. *Cumulative transpiration, total evaporation, drainage, rainfall and net rainfall during the dry period mid-December 1974 to mid-March 1975*



E_o
Total evaporation
Transpiration
Drainage
Rainfall
Net rainfall (rainfall-interception)
4·8 mmd⁻¹
3·36 mmd⁻¹
3·58 mmd⁻¹
CUMULATIVE WATER mm
0
100
200
300
400
500
20
40
60
80
DECEMBER
JANUARY
FEBRUARY
MARCH
TIME t DAYS FROM START OF EXPERIMENT

are in agreement with the long-term estimates from 'water year' balances. Figures from the tea catchment at Kericho are also being compared with the results from the zero flux plane and 'Fluxatron' process studies.

Soil moisture project—Kericho, Kenya

The water use of a tea estate at Kericho, Kenya, was measured directly, using the zero flux plane method, described on page 43.

The roots of tea plants extend to about 6 m. To make tension measurements at this depth, pits had to be dug and tensiometers installed horizontally from one face beneath the growing tea crop. Measurements were taken from early February 1974 to mid-March 1975 when bushes were pruned, and for a further five and a half months after. Results from the period mid-December 1974 to mid-March 1975 (a period of unusual drought with soil moisture deficits of up to 380 mm) indicated that transpiration, E, over the period was related to Penman open water evaporation, E_0 by $E = 0{\cdot}56E_0$ up to a soil water deficit of 380 mm. Cumulative transpiration, total evaporation, drainage, rainfall and net rainfall are shown in Figure 9 for this period.

Further *in situ* measurements of unsaturated hydraulic conductivity in the deep homogeneous soil allowed comparisons to be made between the zero flux plane technique and a direct solution of Darcy'sLaw:

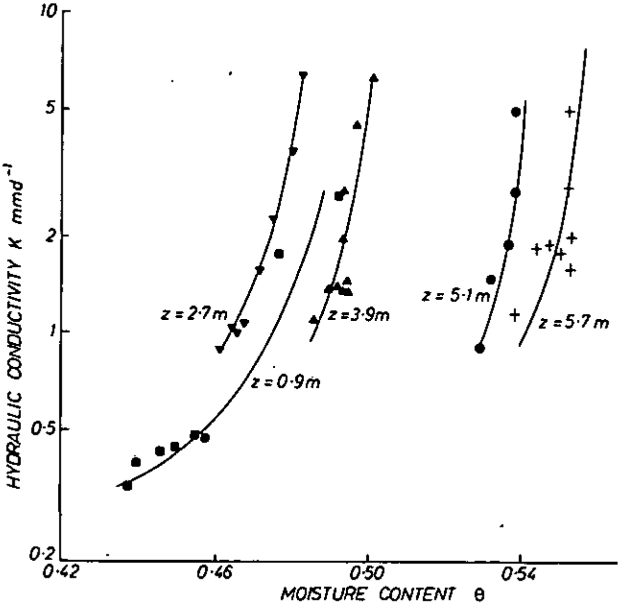
$$V = -K\frac{\partial\phi}{\partial z}$$

where V = moisture flux

K = unsaturated hydraulic conductivity

$\frac{\partial\phi}{\partial z}$ = hydraulic potential gradient

Cumulative drainage, as a function of time, differed by a factor of four when calculated by these two methods, a not unreasonable result when the strong dependence of hydraulic conductivity on soil depth and moisture content is taken into account. Hydraulic conductivity as a function of depth, water content and soil moisture tension is shown in Figure 10. The



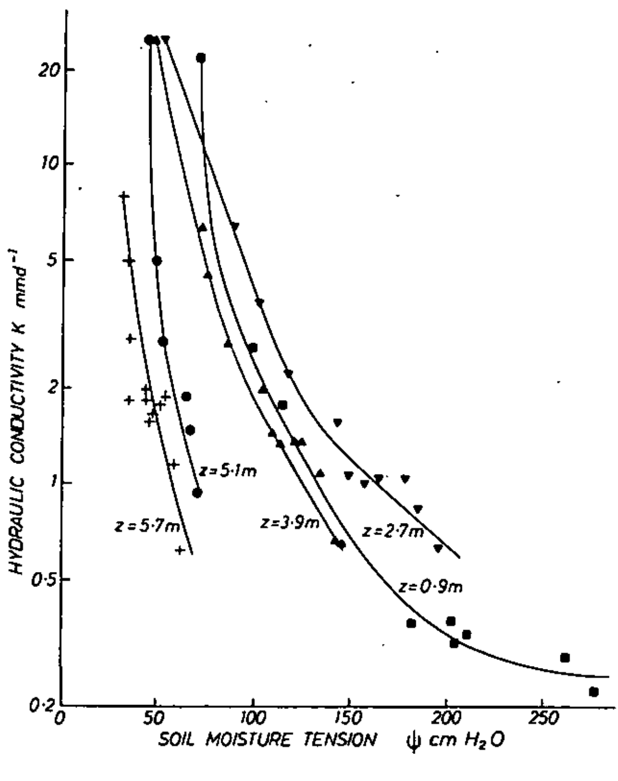


Figure 10. *Hydraulic conductivity as a function of depth and water content (top) and soil moisture tension (bottom)*

Figure 11. *Hydraulic conductivity measurements, Kericho*

photographs in Figure 11 show the area of tea estate used for measurements of hydraulic conductivity, and the tensiometer pit within.

Fluxatron project

This experiment, undertaken in collaboration with the University of Strathclyde, was designed to test the Fluxatron equipment under the conditions of the tea estate environment—a smooth dense level canopy one metre above ground level—and to compare the transpiration rates measured in this way with those from the zero flux plane study described above, with those previously obtained from a lysimeter study and finally, with those obtained in the catchment study. Given that the cumulative figures from the Fluxatron showed reasonable agreement with those from the longer period methods, values obtained from it could be used to quantify more precisely the parameters in the catchment model.

The basis of the study, the 'Fluxatron' equipment, comprises a lightweight, highly sensitive propellor mounted with its axis vertical. Immediately below is mounted a sensitive thermistor bead. Outputs from both are amplified and multiplied electronically to give the net vertical sensible heat flux, H. This, together with measurements of net radiation R_n, soil heat flux G, estimates of changes in canopy heat storage $\triangle J$ from temperature profiles, and energy utilization in growth M, can be used in the energy balance equation:

$$\lambda E = R_n - H - G - \triangle J - M$$

to give an estimate of the latent heat flux, λE, and hence of the evapotranspiration, E. The above expression applies rigorously only when no horizontal movement of sensible heat is present, i.e. under zero advection conditions; this condition was fulfilled by placing the equipment on a site with a 'fetch' of several kilometres over similar tea.

Field experience in 1974 brought to light a few problems with the calibration of the sensors. To help eliminate these problems the equipment was subsequently used alongside other energy balance equipment at Sutton Bonington (University of Nottingham) in the summer of 1975. Corrections are being derived from this comparison for application to the 1974 Kenyan data.

Hydrological Processes

As described earlier in this report, Institute studies of hydrological processes have as their objective the observation and description, in mathematical-physical terms, of the relations between changes of phase and position of water in its course through the land phase of the hydrological cycle, and the energy and forces causing these changes. Work is therefore in progress on the physical and biological controls of evaporation, describing the relation between the evaporation from the plant canopy and the atmosphere surrounding it; on interception, describing the relation between the structure of the plant canopy and precipitation penetrating it; on the flow of water through both the unsaturated and saturated soil layers; on flow over surfaces—particularly those in urban areas—and in channels, whether for natural drainage or for the transport of urban runoff; on the chemical changes taking place in natural (ie unpolluted) water, and on the use of chemical tracers for flow gauging. Progress in these activities is as follows.

Evaporation

Physical controls of evaporation

Most of the research into the physical controls on evaporation carried out by the Institute in past years has been concerned with studies of evaporation from forests, and has been concentrated in Thetford forest, Norfolk. However, in future there is to be a fundamental change in direction and emphasis of process studies in evaporation. Research activities will be diversified to other types of vegetation, and, at the same time, an increasingly significant part of the available effort will be concerned with the development, testing and application of simple instrumentation capable of providing a worthwhile measurement of evaporation for hydrological applications. In view of this change, it is convenient this year not only to describe recent work at Thetford, but also to review the Thetford project as a whole, and outline some of the more important results it has produced.

The project was conceived with fairly limited objectives, but over the first few years, when most of the experimental work was concerned with instrumental and systems development (Stewart and Oliver, 1970; Oliver and Oliver, 1973), the project grew in scope and purpose.

It was clear that there was a need for fundamental research into the processes involved in the interaction between vegetation and the air mass above it. It was expected that observations near a forested surface would provide a more rigorous test of the validity of existing meteorological theory of the turbulent boundary layer, generated by the wind, above and within vegetation. At the same time, detailed observation of meteorological and biological parameters would test the validity of the (then existing) theory of the vegetation/atmosphere interaction.

This aspect of the work has been particularly successful. A theoretical estimate of the change in wind direction between the top and the bottom of the forest canopy (Smith, Carson and Oliver, 1972) indicated a value of 30°, which agreed quite well with experimental measurements (Figure 12). On the other hand, later studies of the turbulent boundary layer immediately above the forest (Thom *et al,* 1975) demonstrated fundamental shortcomings in near-surface micrometeorological theory: estimates of evaporation based on the assumption that the relationship between the gradients of windspeed and humidity is the same above a forest as it is over other types of vegetation, will be in error by factors of two or more. Qualitative studies within the canopy (Oliver, 1973; Oliver 1975A) have indicated thermal plumes the existence of which partly explains this phenomenon.

Preliminary results (Stewart and Thom, 1973) provided a tentative verification, in dry conditions, of the existing theory of the vegetation/atmosphere

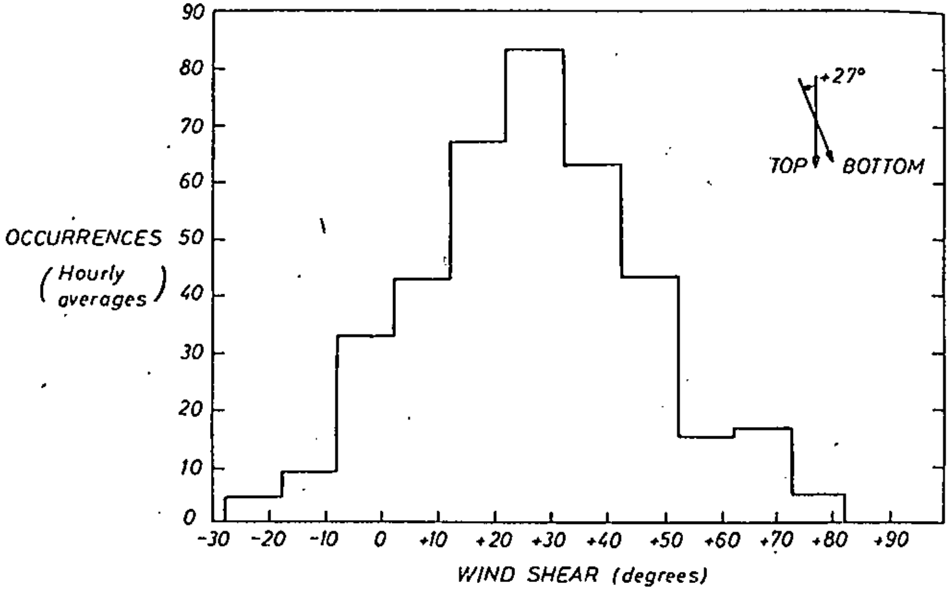


Figure 12. *Frequency distribution of wind shear*

interaction, after it had been extended to allow for differences between the aerodynamic resistance for momentum and heat fluxes. However, later work revealed the expected failure of this theory in partly wet conditions (Shuttleworth, 1976A), and stimulated theoretical work (Shuttleworth, 1975, Shuttleworth, 1976B) which has given rise to a new one-dimensional theoretical description. This theoretical work considers in detail how the behaviour of all the individual pieces of a canopy can be combined mathematically to create an equation describing the behaviour of the vegetation as a whole. It demonstrates how previous simple models, which regard all the evaporation as occurring at one level in the canopy, are related to the complex numerical-simulation models that have been used in the past; and, in so doing, makes explicit (in mathematical terms) the assumptions made in such simple models. The work suggests how the presence of water on the surface of the vegetation might be allowed for, and introduces the idea that the transfer of *all* properties, from vegetation to the atmosphere, is subject to a *surface resistance*.

When the project first began there was considerable speculation regarding the possibility that evaporation from forested surfaces could be enhanced by large-scale advection, *ie.* by drawing in energy in the form of warmer air from the area upwind of the forest. The suggestion was discounted by a great many metcrorologists, primarily because the existing experimental evidence was not conclusive. The Thetford project has provided (Stewart, 1976A) direct and unequivocal evidence for the existence of medium-scale energy advection in wet conditions, even over forests the size of Thetford (large by British standards). Although at present unique (since no similar study has so far been made) this result is of profound significance to hydrology. It emphasises the importance of the interception process for tall vegetation, and is fundamental to an understanding of the difference between the evaporation loss from tall and short vegetation.

Knowledge of the meteorological and micrometeorological characteristics of the forest environment is quite recent: only in the last few years have studies, like the Thetford project, provided the necessary meteorological measurements. Although not a primary objective of the programme, a great deal of information of this type has come out of Thetford work. Most of the results have concerned the observation of windspeed and its effect on the forest environment (Oliver, 1971; Oliver, 1974A; Oliver, 1974B; Oliver and Mayhead, 1974; Oliver, 1975B) while others have investigated the radiation environment and the temperature variations in a forest stand (Stewart, 1971; Shuttleworth, 1974).

One of the fundamental objectives of the project was to provide measurements of the then unknown *surface resistance* of a pine forest and to investigate experimentally the (speculative) correspondence between *surface resistance* and bulk *stomatal resistance*; and in so doing to obtain knowledge and experience for use in formulating improved practical models of the evaporation from natural surfaces. A great deal of the available effort has been concerned with this work. The *median* value of the measurements of surface resistance for Thetford Forest (Figures 13 and 14) exhibits little

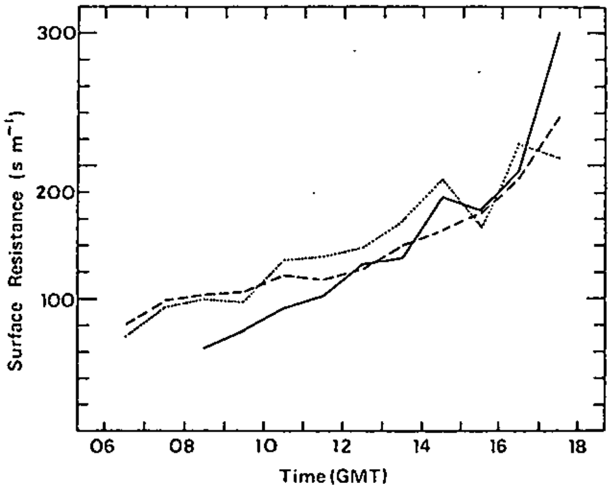


Figure 13. *The diurnal variation of median surface resistance for groups of dry days*

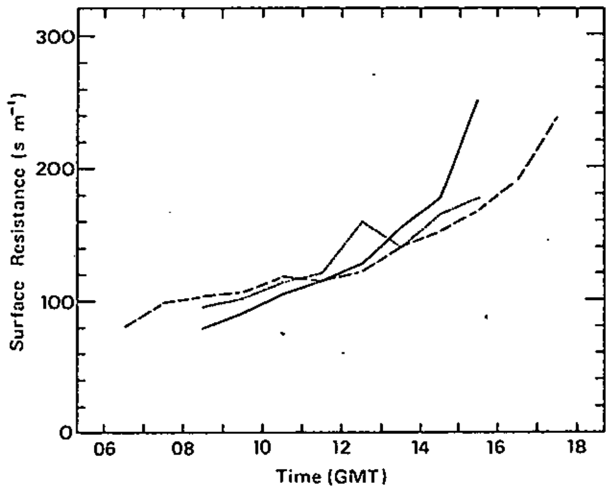


Figure 14. *The diurnal variation of the median surface resistance at different seasons of the year*

variation from season to season and year to year (Gash and Stewart, 1975): a result which is currently being used in an attempt to model evaporation from Thetford forest.

Over the last year, an attempt has been made to extend the Penman equation to make some allowance for variation in the surface roughness of the vegetation and the control it exerts on evaporation by virtue of its stomatal resistance (Thom and Oliver, 1976);

other peripheral studies have been orientated towards improving instrumentation and understanding the errors involved in the experimental methods used in the project (McNeil and Shuttleworth, 1975; Stewart, 1976B).

Of the several fundamental objectives behind the Thetford project, only the requirement to establish (or otherwise) the equivalence of *surface* and *stomatal* resistance remains unfulfilled, although Stewart and Thom (1973) went some way towards this. At the present time, a collaboration is in progress with a group from Edinburgh University, who are making the parallel biological measurements, which will allow such a comparison. At the same time micro-meteorological data are being collected above the forest at two sites two km apart, to provide evidence of the representativeness of the measurements and additional information on advection: while, for the first time, measurements are being made of the forest's carbon dioxide uptake.

Biological controls of evaporation

A better understanding of evaporation control by plants is essential in determining the evaporative characteristics of different types of vegetation. In some cases plant physiological methods may be the only means of making any progress, and for this reason, studies of tree physiology are under way at Plynlimon and Thetford; activities at both these experimental sites are described separately.

The work at Plynlimon is designed to provide estimates of transpiration and an understanding of how trees (in the first instance, Norway spruce) are able to control their transpiration. Evapotranspiration estimates are made using the Monteith-Penman equation. The climatological variables needed as inputs to this evaporation equation are available from an automatic weather station sited at the top of an aluminium tower in the forested Severn catchment. This tower also serves to gain access to the tree crowns as average stomatal resistance of the tree canopy is needed in the equation. This resistance is obtained from individual shoots using a stomatal resistance diffusion porometer built for the Institute at the Botany Department, University of Aberdeen. A description of this type of equipment is given by Beardsell *et al.* (1972). The sampling pattern encompasses variability in resistance due to height in the canopy, shoot age and shading. The average stomatal resistance is computed from the stomatal resistance measurements and a knowledge of the distribution of leaves in the canopy from whole tree sampling. A check on the seasonal changes in needle loss from the trees is made by monthly litter collections in litter cans close to the sampling tower.

The estimates of evaporation made using the Monteith-Penman equation are independent of those produced from the neighbouring natural lysimeter (see page 47) with which they are to be compared. The next stage is to discover whether stomatal resistance (the ultimate plant control of evaporation) is controlled by the plant and how this is influenced by climatic variables recorded by the automatic weather station.

The levels of water stress in the shoots themselves may also be important. This, expressed as needle water potential, is measured with the 'pressure bomb' technique (Scholander *et al*, 1965).

The work at Plynlimon was initiated in the spring of 1975; since then stomatal resistance measurements have been collected on a routine basis throughout a summer season and will be continued until at least a full year's data are available. Information on the structure of the tree canopy is nearly complete in readiness for calculation of whole canopy resistances.

In the summer of 1975 direct estimates of water uptake rates by trees were obtained using a technique in which trees are cut under water and the base of the tree left in a 50 gallon container of water from which water uptake rates are measured (see below). Thus, direct measurements of transpiration which can be compared with the lysimeter values. The technique was also useful in a study of the influence of leaf water potential on stomatal resistance, as removal of the soil-root resistance to liquid water movement through the soil-plant continuum often results in a rise in leaf water potential and an alteration in stomatal resistance. Normal forest trees around the experiment were used as controls for comparison.

Other plant physiological work (but on Scots pine) has been in progress at Thetford for a much longer period and has progressed much further. The tree cutting work described above has been carried out in 1973, 1974 and 1975 (Figure 15). Sufficient data are now available on the effects of leaf water status on stomatal resistance (and hence on transpiration) to conclude the series of experiments. The improvement of leaf water status by removing roots under water causes a decrease in stomatal resistance and an increase in transpiration. This effect is only apparent in conditions of higher evaporative demand, since in dull conditions changing leaf water potential appears to have no effect on stomatal resistance. This

Figure 15. *Trunks of trees cut off under water*

work is supplemented by another experiment in which irrigated trees were compared with unwatered trees; leaf water potential is raised by irrigation and stomatal resistance is lowered.

Trees used in the main cutting experiments were allowed to continue to transpire after removal from the water drums to determine the usable water stored in these trees. This was required to throw light on a problem which arose during earlier soil physical work at Thetford (page 44) when estimates of evaporation by a soil water balance method during a three-week dry period in June were about 1 mm day^{-1} less than those made by the micrometeorological methods (page 33). A possible explanation of this discrepancy was that water stored in trees was supplementing water abstracted from the soil to make up the transpiration total. This quantity would be excluded from the soil physical estimates but would be included in the micrometeorological ones. The results obtained from drying of trees showed, however, that the quantity in store was insufficient to account for this discrepancy.

Another possible explanation is that deep roots running through the upper two metres of sand into the chalk beneath bypass the zero flux plane so that water taken up by such roots is overlooked by the soil physical method. This explanation has been examined in two ways. The first involved the excavation of an extensive trench to expose the deep roots of eight trees. This showed that only a very small proportion of the total root mass actually reaches the upper chalk, suggesting that this would provide only a limited pathway for water. In another experiment measurements of stomatal resistance (measured with a diffusion porometer) of trees were made after various degrees of root pruning. The ultimate aim of the pruning was to leave just the tap root unsevered from the trunk. Progressive cutting of the roots produced no significant effect on stomatal resistance (and hence probably transpiration rate) until the stage when only one lateral root remained together with the tap root. This experiment suggests that tap roots are capable of supplying the tree adequately with water, although conversely, there is evidence from the pit and other root excavations that only about 50% of the trees have tap roots of sufficient depth or size to be able to function in this way.

Interception

Measurements of the loss of rainfall input through its interception by forest canopies are under way at Thetford and Plynlimon—sites chosen as having two very different climatic regimes. The measurements, calculated from the difference between gross rainfall and throughfall plus stemflow, are an important component of the forest water balance. For example, of the 595 mm of rain which fell at Thetford during 1975, 214 mm were intercepted and re-evaporated before reaching the soil. Such direct measurements are being compared with estimates of the interception loss derived solely from measurements of meteorological variables. Firstly, a physically-based model developed at Imperial College is being tested with data recorded by automatic weather stations mounted above the forest. The results of this comparison indicate that the net rainfall reaching the soil can be estimated to an accuracy of better than ten per cent. The next objective is to establish with what accuracy this method can be applied to produce estimates of the interception loss from forests, using data taken not over the forest but at a meteorological station some distance away.

Interception work at Plynlimon suffered a minor setback when the site selected in the Hore subcatchment was rapidly defoliated by saw-fly larvae. A second site just outside the experimental catchment area has now been equipped with four canopy gauges, 18 eight-metre throughfall troughs and 15 stem flow gauges, see Figure 16. Climatic data are provided by two automatic weather stations mounted on towers above the canopy as shown in Figure 29. Repeated difficulties were encountered in operating a highway system of logging multiple gauges in a very hostile environment. This system was finally abandoned in favour of a less-sophisticated but more rugged method, but not before the former method had shown that the

Figure 16. *Part of the interception site, Plynlimon, showing troughs and a stem gauge*

magnitude of stem flow exceeded anticipated amounts. In addition to the main site, seven auxiliary sites were established within the catchment area sampling different altitudes, slopes and aspects. These are equipped with seven four-metre throughfall troughs delivering a catch into separate storage bins and four stem flow gauges, likewise collecting their catch separately.

Unsaturated soil water flow

Soil moisture fluxes in the unsaturated zone

Practical methods of measuring moisture fluxes in unsaturated soil are needed for many different applications—the monitoring of recharge to groundwater, for instance, or for estimating actual evaporation by a crop independently of meteorological or lysimetric measurements, or for following the movement of pollutants in the unsaturated zone.

The Institute has been concentrating on developing the zero flux plane technique, which depends on identifying a depth at which the vertical hydraulic potential gradient (and hence the soil moisture flux) is zero. Soil moisture changes, above and below this depth, represent unsaturated fluxes to evaporation and drainage. Soil water potentials are measured by porous pot tensiometers and the soil moisture content by neutron probe.

A prerequisite for a successful project of this nature is reliable and accurate instrumentation. The Wallingford neutron probe has proved itself in this respect but early attempts to measure hydraulic profiles showed that work was needed to find a suitable design and operating procedures for tensiometers. A cheap and reliable design of manually-read tensiometer has been developed and much operating experience obtained; the computer system for processing and manipulating tensiometer data is described below.

Currently, experiments are in progress at three sites within Thetford forest. The annual rainfall of the area averages 600 mm, with a total E_T value of about 500 mm. The sites lie on sand ($\sim$ 1m) overlying chalky drift ($\sim$ 2 m) overlying Middle chalk. The main part of the project is at the same site as the evaporation and interception experiments described earlier; comparison is thus possible between micrometeorological and soil moisture based estimates of evaporation from Scots pine. The second site is in a grass clearing about one km from the main site and the third some eight km north of these in a Corsican pine stand near to Feltwell. While the groundwater table is at a depth of about 35 m at the first two sites, at Feltwell there is a possibility that the trees are abstracting directly from the relatively shallow groundwater (about 10 m depth). This is being investigated using newly developed pressure transducer tensiometers, mounted in a borehole just above the water table to measure the hydraulic potential gradient in this zone.

A comparison between groundwater level fluctuations and drainage from the forest area using a simple model has already been published (Cooper, 1974). In order to refine this model further three extra observation boreholes have been drilled within the forest.

Computer programs have been written to calculate soil moisture fluxes at any chosen depth given zero flux plane depths and moisture content measurements over a period. They are being used to compute evaporation and drainage from each site throughout the year. A graph of cumulative evaporation and drainage from a forest and grass site through the year is shown in Figure 17.

A flexible and versatile suite of programs has also been written for the handling of large volumes of field tensiometer data. Although some quality control of the data is possible in the programming, much of it must be done manually, hence the programs display the data in tables and graphs to make this work easier and for use in further analysis. The programs offer a choice of (a) tables of the readings of the tensiometers together with the calculated total and matric potentials, and a line-printer plot of the potential profile, (b) a similar graph plotted on the Calcomp

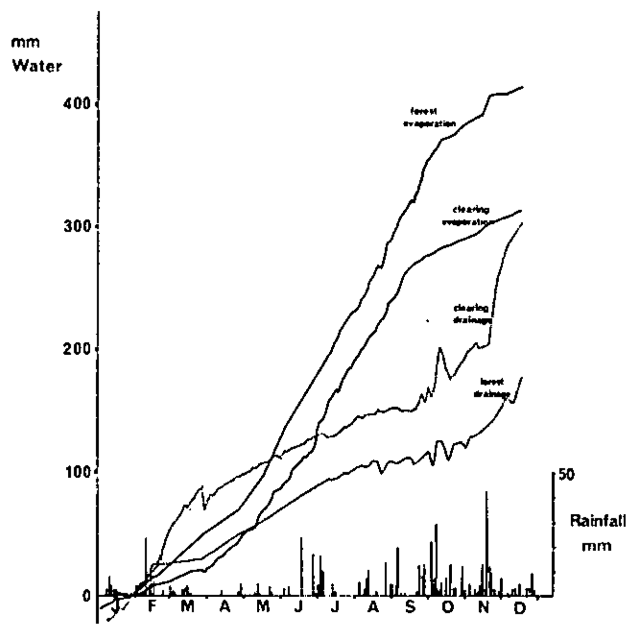


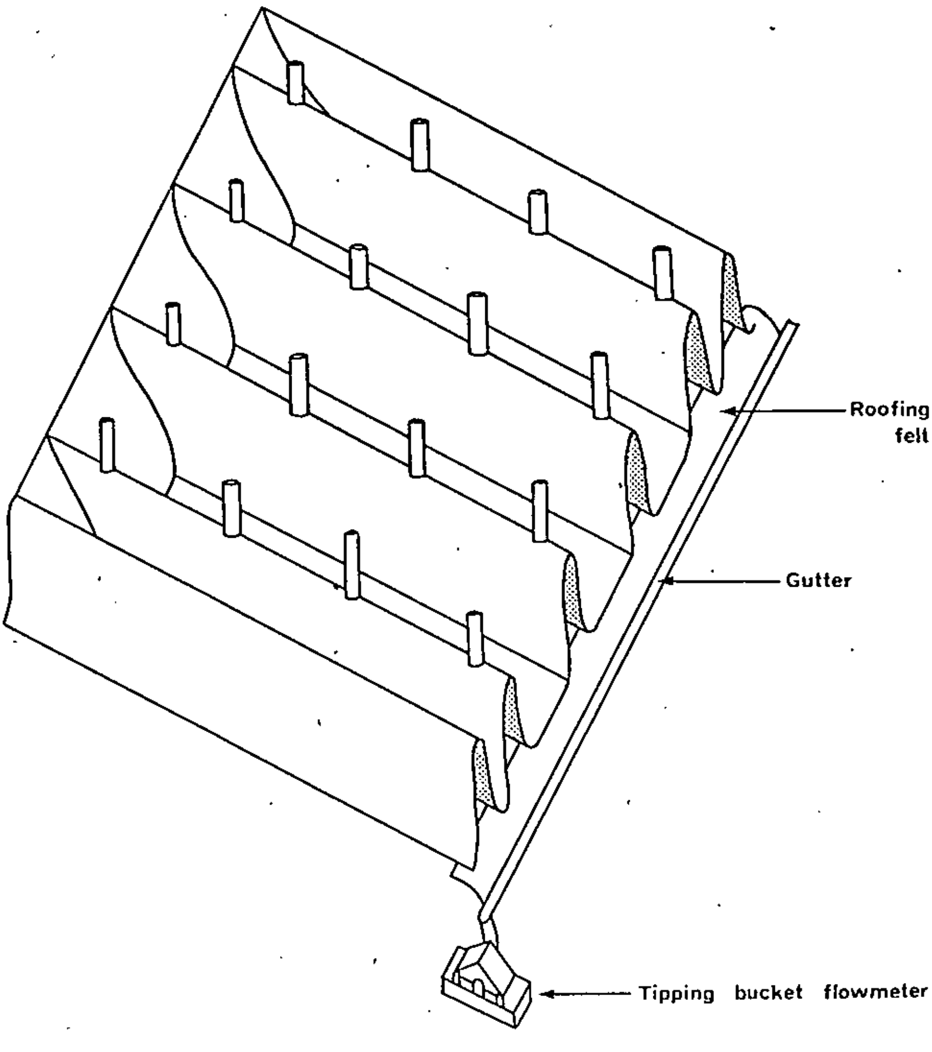
Figure 17. *Cumulative amounts of drainage and evaporation from one forest and one grass clearing site derived by the zero flux plane method for 1974. Graphs have been matched at zero on 30th January*

graph-plotter, (c) the potential profiles plotted in sequential date order for periods of a year or less or (d) a time-series graph of the data together with the relevant rainfall bar-chart. Both (c) and (d) are plotted on the graph-plotter.

Process studies for modelling catchment response

Models of catchment response are being synthesised

Figure 18. *Diagram of forest net rainfall gauge*



from quantitative studies of the components of the hydrological cycle and their interactions. At present, water losses from a forest 'natural' lysimeter in the Severn catchment at Plynlimon are being investigated. The lysimeter has been in continuous operation for two years during which time soil water drainage, changes in soil moisture, soil moisture tension, rainfall and net rainfall have been recorded. The net rainfall data (stemflow and throughfall) were obtained by suspending a plastic sheet beneath the canopy—see Figure 18 (Calder and Rosier, 1976).

Measurements of stomatal resistance and leaf water potential were also made during 1975. Given certain assumptions concerning the forest canopy, the lysimeter observations were used to estimate runoff from the experimental catchment of the upper Severn; this compared satisfactorily with flume measurements (Calder, 1976). The total water losses from the lysimeter for 1974 of 1100 mm (760 mm interception loss, 340 mm transpiration) were found to be almost exactly twice the Penman E_0 estimate of evaporation (540 mm) which implies considerable advection of energy into the Severn forest and also demonstrates the importance of interception losses in similar high rainfall districts. Operational methods are now used to derive surface resistance, aerodynamic resistance, and other canopy parameters from the lysimeter observations and automatic weather station data.

Water movement and losses from grass slopes are also being modelled from measurements taken in the Wye catchment. A feasibility study is in hand to investigate the possibility of using large chamber vapour flux measuring devices in conjunction with fibreglass monolith lysimeters, already in operation, to compare the behaviour of the crop inside the lysimeter with that outside.

Saturated soil water flow

Shallow groundwater in flood plain deposits

One of the largest expanses of reed in the South of England is at Thatcham, Berkshire, covering an area of 0·5 km^2 adjacent to the River Kennet. The reedbed was formerly of commercial importance as a source of thatching material but has fallen into ruin through the neglect of irrigation ditches. Thatcham reedbed, even in its decayed state, is a habitat for a large number of plant, insect and bird species of scientific and rarity value. The high water table, particularly in spring, on which the reed and its fauna depend, is further threatened by the proposed extraction of gravel from part of the site. The Insti-

Figure 19. *Thatcham reed beds*

tute was commissioned by Newbury District Council, in co-operation with the Nature Conservancy Council, to monitor the effect of gravel extraction on groundwater levels.

When the study was first discussed the gravel operations were believed to be imminent. However, extraction has not yet started, allowing us to collect several months of background data which will be useful in establishing the natural fluctuations of the water levels in the reedbeds. Ten shallow boreholes have been installed and water levels measured at fortnightly intervals. To determine the amount of water available for future irrigation of the reedbeds, the flow in ditches traversing the area has been measured by the velocity-area method.

The borehole records show a rise in the water table in some areas over the period August 1975 to February 1976, but by no means does this equal the winter rise, culminating in standing water on the surface, which is necessary to sustain a healthy reedbed. Modelling studies should show whether this was merely an effect of the unusually dry autumn and winter, when rainfall at Thatcham was only some 70% of the average.

Surface runoff and channel flow

Erosion and sediment transport

These studies have been designed to investigate the effects of afforestation on erosion and sediment transport by gauging suspended sediment and bedload from two nearby catchments: the grassland Cyff and forested Tanllwyth. Sources of sediment supply to both rivers were calibrated by means of small rectangular weirs and associated bedload traps (see Figure 20). Automatic liquid samplers have been used for suspended sediment calibrations at a number of representative sites. Erosion pins have been used where the above monitoring systems were inappropriate, eg channel banks.

Fieldwork for the NERC Research Student terminated in Summer 1975 but measurements are continuing on a routine basis. Over two years of data on bedload, believed to be unique at this scale, will form the basis of a PhD thesis.

Data analysis is only at a preliminary stage but shows that a regression model is adequate to describe gross yields of bedload, using discharge hydrograph variables as predictors. Velocity (energy) factors are therefore dominant but residuals may be explained by sediment availability. This is in turn controlled by the sequence of flood events of various return periods. Storage of bedload in the channel system is considerable and has been estimated.

Differences in sediment yields between the two types of land-use are marked, the forested catchment producing nearly four times as much sediment as the grassland. Attempts are being made to separate morphometric causes of this difference from land-use

Figure 20. *Emptying the Cyff bed-load trap*

causes and an intensive study of forest ditching is being conducted.

Urban hydrology

Work is continuing on an investigation into rainfall-runoff relationships for partially and fully urbanised catchments. The research programme has 2 objectives.

The first is geared to the requirements of designers of storm sewers. Studying the rainfall-runoff process in urban areas should provide an improved model of the above-ground phase of urban runoff. This will then be available for incorporation in a new sewer design method being developed at the Hydraulics Research Station. Existing data derive from sewer measurements of water level; they include the effects of pipe flow routing. Such data are being analysed to yield prediction equations relating runoff *volume* to catchment and storm characteristics but they are inadequate for the study of the attenuating and delaying effects of the above-ground system alone. Therefore, following the development of a meter designed to monitor discharge through a road gully, a new data collection programme involving catchments at Bracknell, Stevenage and Southampton is planned for 1976/77.

The second objective is to report on the effect of urbanisation on hydrograph characteristics in natural and improved watercourses. A literature review will be followed by analysis of existing data to yield prediction equations relating unit hydrograph parameters and runoff volume to catchment characteristics. These will be similar to those given in the Flood Studies Report but will have been developed specifically for the urbanising situation.

In connection with this work, we have been fortunate in being able to monitor the changing runoff regime as building proceeds at Milton Keynes. A rain gauge network and a flow measuring station on the main sewer record the rainfall-runoff translation process from impervious surfaces such as roads, roofs and gullies. Aerial photography is being used to record the changing pattern of the impervious cover, as shown in Figure 21.

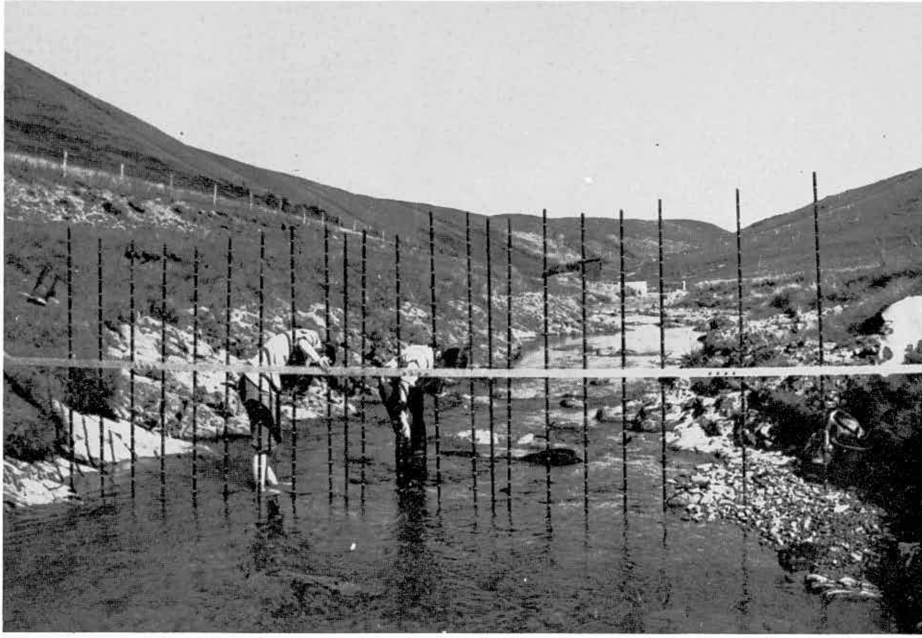


Figure 22. *Channel cross-section measurements in the Wye catchment*

Figure 21. *Aerial photographs of urban development at Milton Keynes, showing progressive impervious cover*

Surface and stream channel characteristics

A programme of field mapping of hydrological domains based on vegetation communities in the Wye catchment has been completed. All major open stream channels in the experimental catchments have been surveyed in cross-section at 100 m intervals (see Figure 22). Thus, a basis has been established for modelling runoff production during storms and the routing of slope runoff in channels. Bankfull channel capacities have given useful information about flood runoff zones in the catchments since the relationship with catchment area does not increase linearly downstream.

The data collection programme for typical runoff domains in the Wye catchment has been completed and the recorders moved to the Severn, where the effects of forest draingage will be calibrated. A naturally-eroding peat catchment (the Upper Severn) is also being studied. A corollary of the study of forest drainage has been the selection of two farm sites outside the catchments where tile drainage schemes will be implemented shortly; this practice is now common in mid-Wales but its hydrological effects cannot be assessed in the Wye catchment where only old open drains exist.

At the request of mathematical modellers, attempts have been made to derive individual parameters including infiltration capacity, hydraulic conductivity of peat, soil pipe drainage factors and channel routing factors. Time-of-travel studies with fluorescent tracers have proved that the fall-and-pool sequences of the upper catchments produce a markedly non-linear decrease in travel time with increasing discharge. Individual studies of separate reaches are now proceeding to ascertain why.

Chemical dilution gauging

Work at the Institute on the chemical dilution gauging method has concentrated on three possible sources of systematic error in the results: loss of tracer, failure to achieve a steady concentration of tracer in the stream, and unsteady discharge. The fourth source of bias, poor mixing in the stream, can be detected by a good sampling technique, and eliminated by a suitable choice of mixing reach.

An intensive gauging exercise by teams from the Institute and the Water Research Centre (Medmenham) was carried out on the River Avon at Christchurch in April 1975, when an ultrasonic gauging station at Knapp Mill (O.S. grid ref. SZ 154943) was checked by both current metering (velocity-area method) and dilution gauging, using sodium iodide injected 850 m upstream. The flow of 29 m^3/sec was the largest yet gauged by the constant rate injection method, and each gauging required the addition of 25 kg of sodium iodide over a period of 5 hours to raise the iodide concentration in the river by 40 μg/litre.

The tracer was injected by a Mariotte constant-head vessel feeding into the inlet of an electric centrifugal pump, which delivered two litres/sec of river water plus tracer to a perforated pipe stretched across the river. Samples were drawn by a multi-channel peristaltic pump from a grid of 50 points on ten vertical stakes driven into the bed at the gauging station. In this way the two-dimensional distribution of tracer at the sampling section could be investigated.

The comparison of dilution gauging with the other methods was intriguing—a typical result was 28·6 m^3/s for dilution gauging, 24·0 m^3/s for current metering and 25·2 m^3/s for the ultrasonic method. Although the higher figure for the stream discharge given by dilution gauging immediately suggested loss of tracer, which is most likely to occur in the finely divided sediment load of the river, investigations of iodide uptake on various sediments showed that sorption by inorganic materials was insignificant. These experiments are described in more detail in the hydrochemistry section.

The constant rate injection method relies on the achievement of steady conditions at the sampling section, while the integration (gulp or sudden injection) method requires the whole of the response curve to have passed the sampling section during the sampling period. The time taken depends on the rate of movement of tracer through the gauging reach. At the sampling section, particles of stream water will have had widely varying times of residence in the gauging reach. These residence times form a statistical distribution which is assumed stationary for steady flow. The residence time distribution $E(\theta)$ is such that any finite sample taken at the sampling section contains a fraction $E(\theta)\,d(\theta)$ of water particles with residence times in the interval $(\theta,\ \theta + d\theta)$. Experiments are being performed to determine the variation of the residence time distribution with discharge for a typical gauging reach on a mountain stream. The distribution is obtained in the field by measuring the response of the stream at the sampling cross-section to an instantaneous injection of sodium chloride at the upper end of the reach. The increase in tracer concentration in the stream (about 25 mg/litre on average) is measured as an increase in electrical conductivity. The residence time distributions obtained to date for the 33 metre reach have been fitted to a random walk function.

$$E(\theta) = \frac{\omega^{\frac{1}{2}}\tau}{\sqrt{\pi}\,(\theta - T)^{3/2}} \exp -\omega \left(\frac{(\theta - T - \tau)^2}{\theta - T}\right)$$

where ω, τ and T are parameters of the curve. The results are encouraging (Figure 23). If this model holds for future experimental results, it will be possible to determine the variation of the parameters of the function over a wide range of discharge and for different reaches, and to provide for a field gauging an accurate estimate of the time required to establish steady conditions at the sampling point.

Dilution gauging is described by British and International Standards as a method for determining *steady* flow. Hydrologists have always assumed that, as in the case of gauging structures, this condition can be relaxed as long as the flow is not *too* unsteady. A mathematical study has been performed (Gilman, 1975) of the effect of changing discharge on dilution gauging using the continuous injection method. A residence time model was used to determine the downstream concentration of a conservative tracer during the passage of a flood hydrograph, and hence the systematic error of the gauging. It was found that, for the cases investigated, the rising limb of the hydrograph could not be gauged accurately, but gauging on the recession limb would show little error.

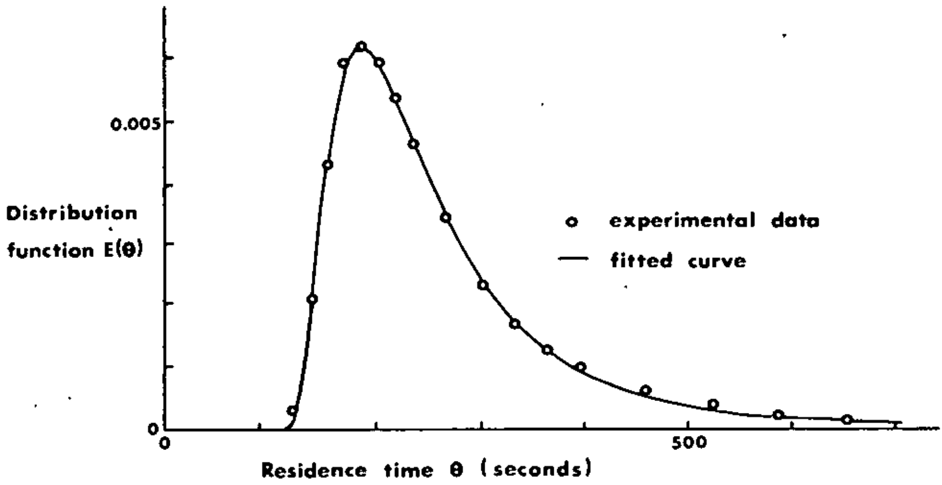


Figure 23. *Comparison of random walk model with distribution of residence times in a short stream reach*

Work now progressing on the error incurred by gauging on the recession limb of the hydrograph, the situation encountered most often in practice, shows that for small rates of fall of discharge the error is of second order in the rate of change of discharge, but depends also on higher derivatives of the discharge. It is expected that this systematic error will be shown to be small for most field gaugings, and that this work will result in a simple method for estimating the error for conditions encountered in the field.

Hydrochemistry

Chemical elements dissolved in natural waters can exist in one or several forms which differ either in their oxidation state (eg iodine which is found as both iodate ions and iodide ions) and/or their complexed state (eg Zinc which can be present as Zn^{2+}, $ZnCl^{1+}$, $ZnCl_2$, ZnOHCl ions and chelated with organic material). The form of a chemical element is an important factor in determining its reactivity in natural systems. It is because of this importance that the Institute's chemical work is at present concerned with speciation problems. We are concentrating upon the speciation of silicon and iodine, the former because of its control of the solubility of silicates and silica, and the latter because its speciation is controlled by a redox couple which is an important factor in assessing its use as a tracer for dilution gauging. Chemical systems that include a water/sediment interface are also under investigation because such reactions are important in both a water resources context, where they can control the quality of abstracted water, and in dilution gauging, where significant sorption of tracer on suspended material in the river could vitiate a gauging.

A method is being developed to determine the silicon species in natural waters using the different reactivities of these species towards an acidic molybdate reagent in which molybdosilicic acid forms. Progress in its development has suffered from the previous lack of understanding of the chemistry of the silicate/molybdate reaction. Our studies during the last two years have enabled us to define these reactions rigorously, and as a result two methods for the determination of silicate have been developed. Twenty-seven samples of upland river water from around the sources of the rivers Wye and Severn, when analysed by these methods, produced mean silicate values of 950 ± 3 μg l^{-1} and 949 ± 3 μg l^{-1}. Our recent publications on this subject (Truesdale *et al*, 1975; 1976) will be of direct value not only to the Institute, but also to many hydrochemical, geochemical and industrial laboratories.

Table 3. *The percentage iodide and iodate sorbed on to stream and river sediments in their associated fresh waters for a suspended load of 2·0 g l–' and an initial iodine concentration of 40·0 μg l–'.*

The element iodine occurs in a wide range of concentrations in natural waters. Although it can be present in a number of different forms, little is known of the factors that control its chemistry. Investigations of this element began two years ago when sodium iodide was introduced as a dilution gauging tracer. A rapid (50 samples per hour) automatic colorimetric method for the determination of the low concentration of iodide used in a gauging (40 μg l^{-1}) was developed at the Institute. The method relies upon the catalysis, by iodide, of the reaction between ceric ammonium sulphate and arsenious acid. This procedure has been extensively used during the past two years (an estimated 10,000 samples) and we have found it to be not only reliable, but also to be accurate and precise. (In the range of concentration 1 to 100 μg l^{-1} iodine the error will be within ±0·36% for 95% confidence). Extension of this method so that it can differentiate between the iodine species (I^-, I_2, IO_3^-) at even lower concentrations is now well in hand. Reactions at water/sediment interfaces are being studied firstly in terms of trace element uptake, with particular emphasis on iodide because of its use in dilution gauging, and secondly in terms of major element uptake which deals with the changes of water quality within aquifers. Investigations of a wide variety of sediments, together with their associated freshwaters, have demonstrated that uptake of significant amounts of iodide and iodate can occur. The results of these investigations are shown in Table 3.

Table 4. *Sorption of iodide and iodate on to peat and iron hydroxide*

The suspended loads used in the experiments are several orders of magnitude greater than those found normally in rivers and hence represent sorptive effects far greater than those anticipated at normal sediment

River	Ordance Survey Grid Ref.	Lithology	Iodide 2 hrs	Iodide 24 hrs	Iodate 2 hrs	Iodate 24 hrs
Kennet	SU506630	CHALK	0·0	8·6	0·0	2·1
Middle Ditch	SU506650	CHALK	0·0	3·0	5·7	5·7
Chalgrove	SU636970	CHALK/CLAY	0·0	6·4	0·0	0·0
Great Haseley	SP613000	CLAY/SANDSTONE	0·0	0·0	14·4	14·4
Thame	SU594987	CLAY	0·0	1·2	0·0	0·0
Chaddesden	SK384372	SANDSTONE	0·0	2·0	0·0	0·0
Lathkill	SK212656	LIMESTONE	0·0	2·1	0·0	0·0
Upper Wye	SN805865	PEAT	8·7	34·3	8·2	27·8
Avon 1	SZ154943	CHALK/CLAY	0·0	0·0	0·0	0·0
2	to		0·0	0·0	0·0	0·0
3	SZ155959		0·0	1·0	0·0	0·0
4			0·2	0·0	0·0	0·0
5			0·0	0·0	0·0	0·2
6			0·0	0·3	0·0	0·0

System	Fraction of 40 g l^{-1} of iodine sorbed (%)				
	Sediment load (mg l^{-1})				
	1·0	10·0	100	1000	10000
Iodide and peat in freshwater	0·02	0·16	1·62	14·69	70·46
Iodate and peat in freshwater	<0·2	<0·2	3·85	20·50	78·25
Iodate and ferric hydroxide (adsorbed)	4·58	26·25	62·15	84·94	94·75
Iodate and ferric hydroxide (co-precipitated)	5·58	34·50	78·74	95·73	99·21

loadings. Nevertheless, the results show that the greatest uptake of iodide and iodate occur with peat. Experiments with various suspended loads of peat were carried out in order to determine iodide and iodate sorption. Freundlich isotherms, when extrapolated to average suspended loads (approximately 2 mg l^{-1}), indicate that less than 0·1% of iodide and iodate are removed from solution at this loading. Other experiments carried out with freshly precipitated iron hydroxide showed that iodate is strongly sorbed whereas iodide is not sorbed. Iodate, therefore, should not be used for dilution gauging of fresh waters, whereas iodide is suitable provided that suspended loads are small.

Analagous studies, performed in the presence of high concentrations of salt, suggested that iodide and iodate sorption could be important in controlling the distribution of iodine in an estuary. Further work will therefore be required before the use of iodide as a tracer in an estuary can be vindicated. In the second group of studies, a method has been developed for determining the major cations adsorbed on clays present in a clay-carbonate assemblage. The method is being refined for the determination of exchangeable cations on carbonate surfaces. It is anticipated that field studies of the effects of cation exchange on water-quality, both in surface and ground-waters, will be initiated shortly. In particular, the effect of saline waters on the surface chemistry of clays and carbonates will be studied.

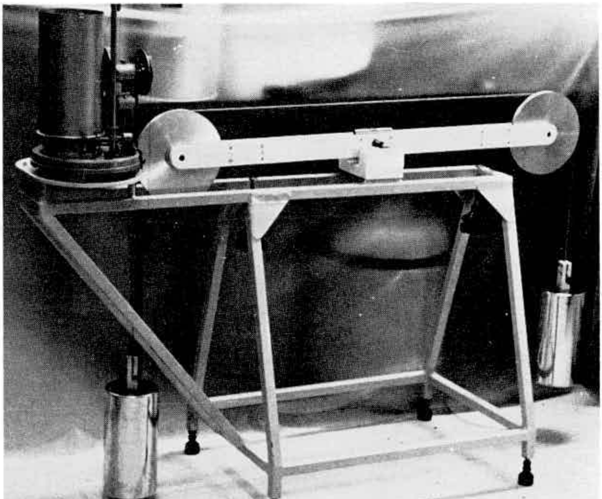


Figure 24. *Aquifer compaction recorder. The anchor weight at the base of the borehole is represented in this layout by the left hand steel weight*

Applied Hydrology

Assessment of resources

The Tehran basin

The objective of this study, carried out for Sir Alexander Gibb and Partners is to look at the groundwater development potential of the Tehran area. It is essential that water supplies are maintained until the commissioning, early in the next decade, of a large reservoir serving both agricultural needs and also supplies to the city of Tehran itself. Intensive demands will therfore be made on the groundwater reserves of the Tehran region in the next few years. Water quality investigations have been carried out in the field and hydrological information collected during the construction of water supply boreholes. Short field visits have been made to study the pattern of snowmelt runoff and recharge into the aquifer and changes in agricultural land use which might affect the evaporation losses. Knowledge of the water balance of the area is being brought up to date by incorporating into a hydrological model all recent measurements of mountain runoff, precipitation on the plain, outflow from the city and water level changes measured in a comprehensive network of observation wells. Proposals for groundwater management will be tested on this hydrological model.

When large amounts of groundwater are abstracted from sediments containing clay, compaction of the dewatered aquifer can occur, causing subsidence of the ground surface. A compaction recorder is to be mounted close to abstraction wells in Tehran to monitor this possible effect. The recorder, shown in Figure 24, measures the movement of the ground surface relative to the upper end of a steel cable which passes down a borehole to an anchor weight at the base of the aquifer. A system of pulleys and a knifeedge suspension ensure that the tension in the cable is constant, while the movement is recorded on a vertical drum water-level recorder. The instrument is based on a design used by the US Geological Survey, but the detailed specification and working drawings were developed from first principles at the Institute. The instrument was subsequently constructed by an outside contractor and then shipped to Tehran for operation by the Tehran Regional Water Board.

Water resources survey of northern Oman

The study area, over 13 000 km^2, can most simply be described as those wadi basins which drain the Jabal Akhdar and Jabal Nakhl. This massive limestone anticline forms a mountain range 125 km long and rises to 3000 m. The moderate though unpredictable rainfall on the Jabal (there are usually several storm periods each year of about 100 mm) distinguishes the region of northern Oman as one of the few areas of the Arabian peninsula where settled agriculture is

Figure 25. *Flash flood approaching wadi gauging station, northern Oman*

possible. In the alluvial areas of the wadi channels, the piedmont and the extensive plains to the north and south of the mountains, traditional systems for exploiting groundwater have ensured a reasonably reliable supply of water for irrigating date gardens and fodder crops. In the last decade there has been some development particularly along the coast of the Gulf of Oman. Pump-sets have been established on most of the hand-dug wells and modern boreholes have been drilled in an endeavour to increase the supply of irrigation water. Cropping patterns are more stable but some new farms using modern techniques are being established.

The objectives of the study were to assess the characteristics of the alluvial aquifers, to determine the major sources of recharge to them and to make a preliminary estimate of their long-term yield. In addition we were to examine the potential for enhancing the rate of replenishment of the aquifers by reducing the losses of fresh water to the sea or to the desert, and to assess the potential of the bedrock as an aquifer.

Very little basic data existed at the start of the study: some rainfall data were available from stations at low altitude; runoff, which takes the form of flash floods, had not been measured; and there were no records of water level changes in the aquifers. The method of study was heavily influenced by this lack of basic data and much of the field work was directed towards establishing instrument networks and collecting primary data before any worthwhile analysis could take place. It was expected that in this varied and difficult terrain accurate measurement of the variables would not be easy and that a qualitative understanding of the processes of runoff and recharge would be needed to underpin the quantitative analysis.

Three broad fields of investigation were established. The first, a study of the surface water hydrology was concerned with collecting sufficient records of rainfall and wadi flows to determine the proportion of rainfall which is available for recharge and to use the limited historic records to estimate long-term recharge and hence potential aquifer yield. The second field of investigation was concerned with the aquifer lithology and characteristics such as transmissivity and storage coefficient with the aim of determining flow through the aquifers in relation to the water table configuration. The third and final part of the study was concerned with the sources of water available to the villages throughout the area. It was anticipated that the balance between resource and use would be close and that abstractions for irrigation would play a significant part in the water balance of the alluvial areas.

In general terms we were able to develop a model of the rainfall/runoff/recharge process, which could be supported by independent estimates of groundwater flow, and which was consistent with the pattern of water use for irrigation. This was particularly gratifying since a prolonged drought persisted through half the study period and water availability reached its lowest level for many years. Fortunately 1975 was a year of average rainfall and the model was based on three short periods of storms.

Our studies indicated that recharge in wadi channels and piedmont areas at the mountain foot was invariably more than recharge in the alluvial plains where secondary geological processes such as precipitation of carbonates had given rise to extensive deposits of cemented gravels possessing poor infiltration characteristics and low transmissivities.

The study was carried out in association with Sir Alexander Gibb & Partners, Consulting Engineers.

Santa Elena peninsula

The Institute provided on secondment the team hydrologist for the ODM Santa Elena Peninsula Technical Assistance Project, which covered a poorly developed, partly arid, area of Coastal Ecuador. Advice was given on the improvement of hydrometeorological stations within the area and on the extension of networks of raingauge and climatological stations at a level required for the practical development of agriculture and water resources.

Recommendations were also presented to the Ecuadorian National Water Resources Institute (INERHI) for improving the coverage of agrometeoro-

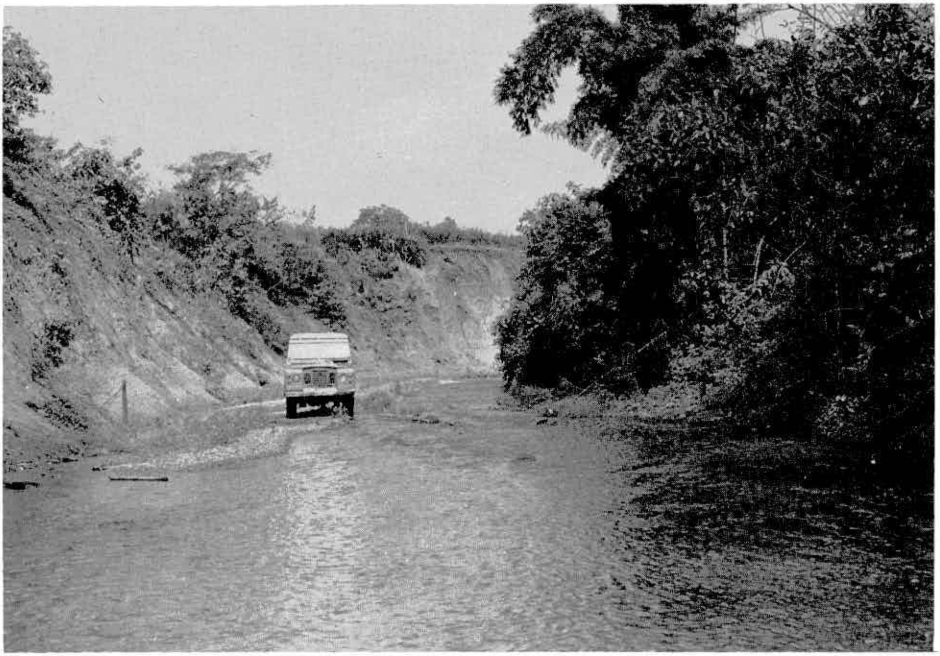


Figure 26. *Inspection of existing stream gauging site, Santa Elena, Ecuador*

logical stations within the cropping zones of the major irrigation projects, both in the coastal lowlands and in the Andean Sierra at altitudes of 3000 metres and above.

The water supply of Guayaquil, the largest city and main port of the country, is taken from the Rio Daule, one of the two major tributaries of the Rio Guayas which drains a large proportion of the coastal lowlands of Ecuador. The pumping station where water is abstracted at present is above the point of furthest penetration of saline water from the Guayas Estuary, but plans for increased abstraction have led to a joint study by the Hydraulics Research Station, Wallingford, and the Guayaquil Municipal Water Board (EMAPG) into salinity intrusion within the Estuary, using modelling techniques already developed by HRS in a study of the River Gambia in West Africa. A search was made for all available flow data for the other main Guayas tributary, the Rio Babahoyo, which joins Rio Daule just upstream of Guayaquil;

these records were analysed at the Institute in a suitable form for the HRS salinity intrusion models.

Mauritius

Records at a number of sites in Mauritius were used in a study of proposed hydroelectric development based on alternative reservoirs (a study for Engineering and Power Developments Consultants Ltd.). The records were extendep by correlation between short-term and long-term rainfall and runoff records, supported by consideration of water balances computed from a comparison of records at a number of sites in the area. The investigation was complicated by the need to allow for past and future extractions of water for irrigation schemes.

Optimal exploitation of resources

River Jacui, Brazil

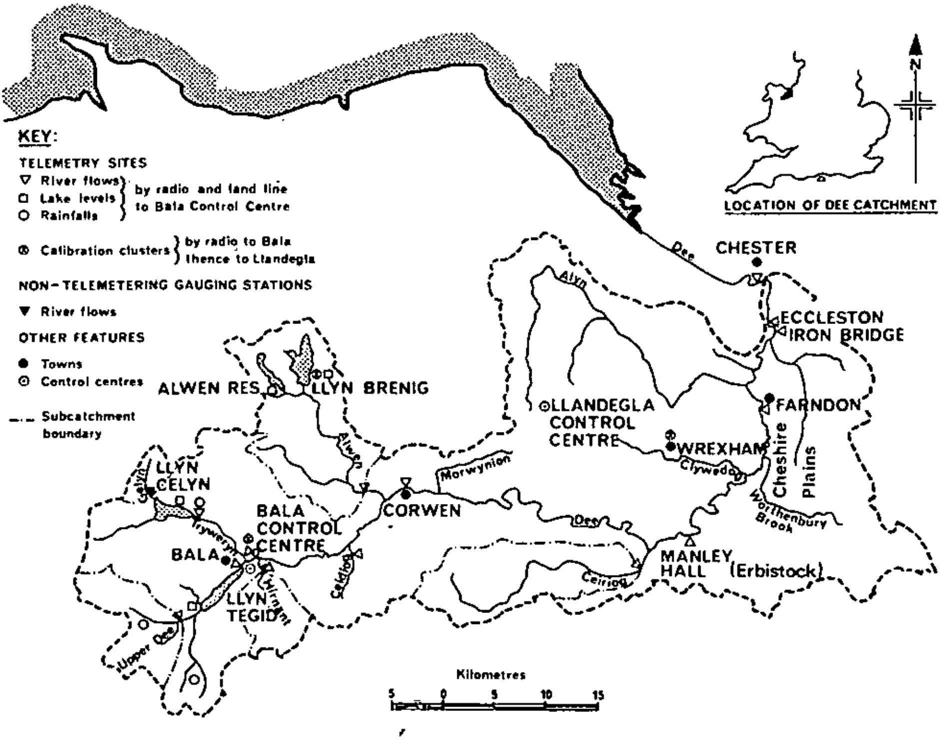
The objective of the River Jacui project is to determine the optimum operating rules for three barrages on a 300 km stretch of river used for the transport of the soya crop grown in the interior of the southernmost part of Brazil, Rio Grande do Sul. The barrages should be operated such that depth of water in the river is maintained above three metres—the draught of the vessels used—for as long as possible throughout the year; as a second objective, the frequency of flooding is to be minimized. Each barrage has a series of individually adjustable gates, the most upstream barrage at Fandango having 40 gates each of two metres width, the barrage at Anel De Dom Marco having four gates of approximately 20 metres width and that at Amaropolis having 84 gates of two metres width. A navigation lock allows the passage of vessels past each barrage.

Two approaches are being used to determine operating rules for the barrages. The first is a trial and error simulation study using a systematic sample of mean daily flows drawn from a reconstructed twenty-year record. A set of operating rules is assumed for each barrage, and for each sampled day backwater curves are computed for each of the three critical reaches of the river to determine whether or not water depths are everywhere greater than three metres. The ratio (number of days in the sample in which water depth falls below three metres somewhere in a reach)/(total number of days in the sample) is then a measure of the efficiency of the operating rules being tested; the operating rules are then varied until the ratio is satisfactorily small. In the second approach, the shallow-water St Venant flow equations are solved by the method of characteristics given (a) an input hydrograph at the upstream end of a reach; (b) an assumed power-law relation between the discharge over the barrage at the downstream end and the difference between the depth of water immediately upstream of the barrage, and the barrage height. Depth of water is calculated at points along the channel and at intervals of time; discharge over the barrage is also calculated, and is used as input data to a similar calculation on the next reach downstream. The computer program for the solution of the St Venant equations could be incorporated at a later date as a subroutine in a dynamic programming optimisation in which the objective function (to be maximised with respect to the three barrage settings, each regarded as a function of time) is the minimum of the three minimum depths, one from each reach.

River Dee real-time forecasting system

Under contract to the Water Research Centre, the Institute of Hydrology has provided a real-time computer model for short term flow forecasting on the River Dee. The system demonstrates the use of weather radar data as input to a hydrological model and the potential benefit to the operation of river regulation schemes of real-time flow forecasts.

A large number of field outstations transmits river level and rainfall information from all parts of the catchment to the computer at half-hourly intervals. The computer is also linked by land line to a weather radar at Llandegla which provides estimates of the half-hourly subcatchment rainfalls, as well as displaying at the Bala control centre on a colour TV monitor the latest picture of rainfall distribution. The



model then uses this information, together with the current rainfall forecast, to produce a 24-hour prediction of flow from the smaller subcatchments of the Dee. A simple rainfall-runoff model (McKerchar, 1976) is employed; it makes the basic assumption of a unique relationship between catchment storage and outflow.

Figure 27. *Map of River Dee catchment*

Using the variable parameter diffusion method (Lowing, Price & Harvey, 1975) developed at the Hydraulics Research Station, the forecast subcatchment flows are then routed down the main channel to Corwen and Manley Hall (see Figure 27). A second model is then used to produce two-day forecasts for the Farndon-Eccleston reach in the Lower Dee where abstractions are made for water supply purposes.

The project is now entering a second phase, in which the sensitivity of the forecast to different aspects of the system will be investigated.

Estimation of flood and drought frequencies

Predicting the flood response of a catchment

Much of this project is concerned with follow-up activities connected with the Flood Studies Report, published last year. Contributions to conferences, teach-ins, lectures, and the giving of advice to users have all taken up much time but have also helped to focus attention on those particular aspects of the Report's recommendations which are most in need of further study.

A case in point is an extension of the unit hydrograph/losses section of the Report. This work had two main aspects, the prediction of runoff volume and the prediction of the timing of runoff using the unit hydrograph. The main aim is to improve the confidence limits associated with these predictions. This requires the collection and collation of further data to sample from a wider range of catchment types, and further screening of event data used previously. The second task is necessary to raise the general level of data quality and is complemented by the addition of recent event data (ie post 1969) to replace rejected material.

Predictions may also be improved by using new independent variables in the regression equations. In this context, an extensive investigation into various indices of average catchment slope is under way. Also, the nature of the soil index proposed in the Report is being re-examined in the light of more detailed information and with the benefit of feedback from the catchment data already analysed.

Within-catchment variation of unit hydrograph parameters could not be explained by any event variables used in the earlier work. Some of the data appeared to support the classical criticism of the unit hydrograph—a linear model is a poor representation of a non-linear system—and some clearly reflected data inadequacy. The uncertainty prompted the conservative recommendation to reduce unit hydrograph time-to-peak by a third when designing against extreme floods. This recommendation may not always be appropriate however, and studies are in hand to refine it, again with the benefit of better quality data.

Statistical models for the distribution of flood flows

Small return period floods

In economic terms, it is often the most frequent floods that are most important. They have been estimated using a theoretical relationship between the peak over threshold and annual maximum flood series. As shown in Table 5 below this leads to an under-estimate of the flood. These results are for eastern and southern England and an explanatory paper is being prepared to show more general results.

Table 5.

Flood recurrence per year	5	2	1	0·5
Equivalent annual maximum return period (years)				
according to flood records	1·06	1·36	1·90	2·89
according to theory	1·01	1·16	1·58	2·54

Seasonal flooding

Agriculturalists are interested in flood frequencies considered separately for both the growing and dormant seasons. Early indications are that the seasonal incidence varies little in different parts of the country although an area in east Scotland shows an interesting divergence from the national pattern. The influence of urban development on augmenting summer flooding is also being studied.

Flooding due to two or more causes

Bivariate extreme value distributions are being used to solve the 'twin hazard' problem. This arises when a line of communication can be cut by two rivers, or where land can be flooded by both tidal and fluvial influences.

Flood survey problems

To suit the special requirements of the extensive land drainage surveys that Water Authorities are producing, standard calculation sheets are being prepared and short-cut procedures have been developed to estimate floods at many points within a basin. Preliminary guidelines to allow for the effect of urbanization have also been prepared.

Follow up studies to United Kingdom Flood Studies

Techniques for regionalising mean annual flood values from catchment characteristics and pooling flood frequency curves are being updated with more recent information from the data which is now held by the Water Data Unit. Special attention is being given to the behaviour of catchments less than 10 km^2 in area.

Short-term consultancy projects

A number of relatively short term investigations involving the techniques and expertise developed for and reported in the Flood Studies Report has been applied to several sites in the United Kingdom and overseas.

Estimates were made of the magnitude and frequency of flooding at drainage crossings for a road design in north-eastern Botswana. The instantaneous peak flows were extracted from the gauging station records, a relationship between mean annual flood and catchment characteristics derived, and a regional flood frequency curve then built up to relate the design flood to the mean annual flood. A somewhat similar study of flood frequency relationships was carried out for three oilfield areas in southern Iran. This work was then supplemented by field reconnaissance to deduce the physical sources of recent flooding and thus provide a basis for flood control.

Projects for clients in this country have tended to be one of three types: flood studies for the reappraisal of existing reservoir dam spillways; design flood estimates as a step in the design of new reservoirs, and river basin flood studies. Reappraisals of existing reservoirs were performed on the Howden/Derwent/ Ladybower system of the Severn-Trent Water Authority and on a small reservoir in north Wales owned by the Welsh National Water Authority. In both cases the estimated maximum flood was computed to check the existing spillway capacity.

Detailed flood frequency studies, up to and including the estimated maximum flood, are often required for reservoir design. Accordingly, we assisted in this way for the proposed Ardingly reservoir in Sussex for the Southern Water Authority and work is currently in progress for the South-west Water Authority on a proposed flood storage reservoir on the River Lowman, upstream of Tiverton.

The Flood Studies Report techniques have twice been applied to river basins as a means of providing the hydrological input to a mathematical flood-routing model developed by the Hydraulics Research Station. Such hydrological input is required for model calibration and also for producing design hydrographs necessary for the design of any capital works proposed. One example, the River Rhymney in South Wales, is cited in the Flood Studies Report. The other case studied was the Lagan basin in Northern Ireland where flood estimates are needed for the design of both agricultural and urban flood alleviation schemes.

A different type of river basin project was the Institute's contribution to a study of the flood hydrology of the lower River Avon near Bristol, part of a project undertaken by Sir Alexander Gibb and Partners for Bristol Corporation. The question posed was what effect would the construction of a barrage on the tidal part of the river have upon the likelihood of flooding further upstream. The basin provides an interesting problem because a major part of the large conurbation of Bristol is situated at the lower end. The basin was divided into five subcatchments, and flood frequency relationships determined for each of them using the pooled regional approach. The discharge hydrographs for these catchments in response to two notable storms were also determined using the unit hydrograph technique.

Formulae are being developed to relate magnitude, frequency and duration of low river flows to catchment characteristics. The data assessment phase of the project is now complete—750 gauging stations have been identified as being suitable for low flow analysis. Most of the data comes from the Water Data Unit although some records have been supplied from gauging authorities directly to complete an archive of 7000 station years of mean daily and monthly flows.

Programs have been written to extract parameters of the flow duration curve, storage-yield relationships, annual minimum series and recession constants from the flow data. A preliminary analysis of the results shows a close relationship between some low flow measures commonly used in water resources design. For example, Figure 28 shows the relationship between the 95 percentile on the flow duration curve and the mean annual one day minima (both expressed as the percentage of the mean annual flow) for 30 catchments. Inter-relationships of this type should

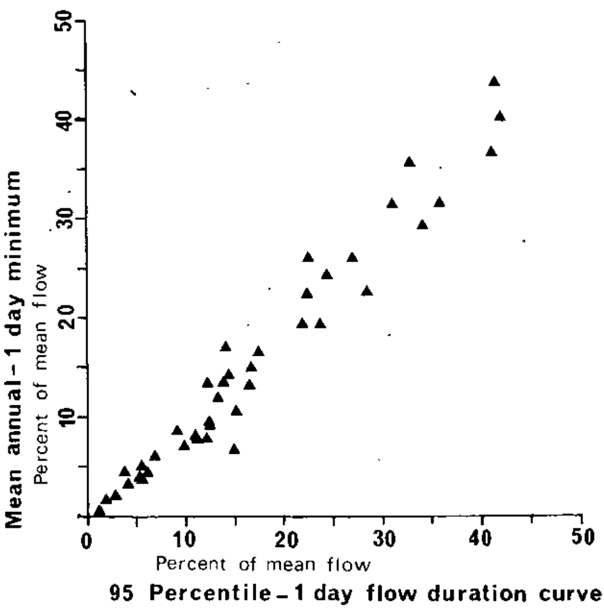


Figure 28. *Relationship between mean annual minima and percentile from flow duration curve*

lead to one flow index being derived from catchment and climate characteristics; other indices can then be derived directly from this.

Recession constants derived from catchments of a single geological type are being used in the development of a 'geology index', one of the catchment variables to be used in regressions equations. The influence of drift deposits is being studied by comparing drift covered with drift-free catchments having similar solid geology.

Instrumentation

Data logging and telemetry

The development of a reliable, field logging system, using the Microdata equipment described in previous reports, has allowed the Institute to install a large network of remote recording stations. The variables monitored in this way range from those of climate and evaporation, through river level to a number of special applications such as interception studies and urban catchment measurements.

The logger records its data, in digital form to 8 bit accuracy, on the familiar small cassettes of modern cassette recorders. It is battery powered and will operate for up to a month depending on the frequency of recording, the type of tape used (C60, C90) and the number of variables sampled; it can accept up to 12 inputs. Where necessary an interface unit with suitable conditioning circuits is used to match the sensors to the logger.

The various applications of the system can be best described by considering types of stations. The automatic weather station (AWS) is now a familiar tool of the Institute's work. It monitors solar and net radiation, wind run and direction, air temperature and wet bulb depression and rainfall. There are stations in operation at Plynlimon (some over the forest canopy, see Figure 29), at Coal Burn, Thetford (also over the canopy) and at Grendon Underwood. There is also a network of stations for non-IH users such as Institute of Terrestrial Ecology, Nature Conservancy, universities, Institute of Geological Sciences and Water Authorities. Overseas, there are stations in South Georgia, Kenya and in the Yemen. Operation of such equipment overseas however is to be undertaken only guardedly, since their complexity may not be in keeping with developing countries' best interests or capabilities.

Figure 29. *Automatic weather station mounted over forest, Plynlimon*

During 1975 considerable effort was applied in writing a range of new computer programs for AWS. These quality-control the data which is then stored on 7-track tape and disc for easy access.

Over the last few years the logistics of AWS use have been a matter of greater concern than technical matters of hardware. Hardware development is complete, but accumulated experience shows how important people are, even in 'automatic' systems. Maintenance, operation and processing, and the communication between operators handling these functions are vital to the reliable return of data. Hardware developments continue, nevertheless, and currently an AWS is being modified for test on the summit of Cairngorm in N.E. Scotland, see Figure 30. The aim of this exercise is to extend the range of the equipment to include harsher and more difficult climates.

Automatic weather stations represent the main use of data logging equipment but during the last year many of the Institute's stream gauging sites were equipped with a level sensor, as shown in Figure 31, developed at the Institute, coupled to a data logger. The sensor is based on a potentiometer system which can accommodate almost any range of level change and discriminate the changes down to 1 mm. The advantage of this system is that it produces a digitised record, unlike the conventional chart level recorders, and that the record can be replayed on the same reader that handles the AWS cassettes. Development of this equipment is complete.

A sensor recently developed for use with the logger for urban catchment measurements uses a 'Dipper',

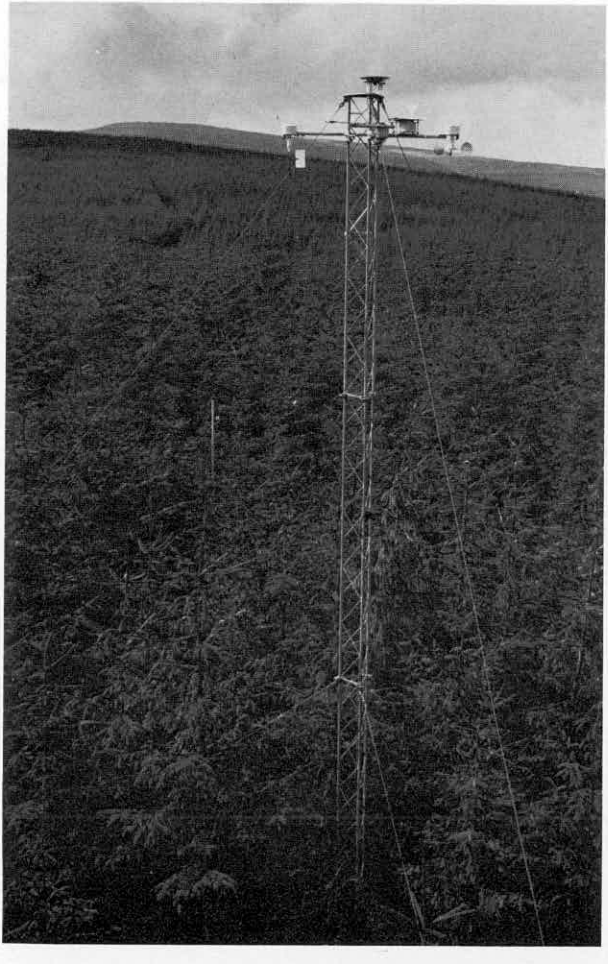
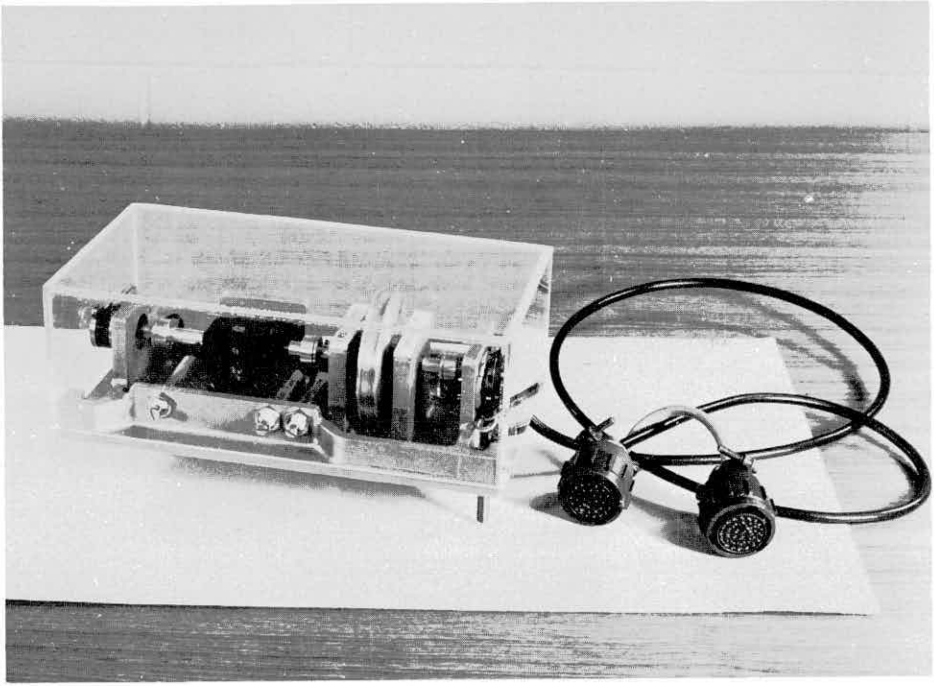


Figure 30. *Erecting automatic weather station on Cairngorm*



a piece of American equipment, modified at the Institute to give a signal output indistinguishable from the level sensor above. This device senses water level in a sewer pipe by lowering a probe until it touches the water. It then withdraws a few mm for a few seconds and then feels for the water surface again. This process continues. In this way float and stilling well are unnecessary and fast, turbulent, water can be monitored. Under development for other urban work, and to be installed at 11 sites, is another sensor for use with the Microdata logger. This monitors the water flowing through gullies by passing the water through a square sectioned pipe in which there is a pivoting flap. The latter activates a potentiometer which gives an output related to flap angle, which is related to flow rate.

Figure 31. *River level sensor*

The Microdata logging system is also being used to record albedo, soil heat flux, soil temperature, stem flow, leaf wetness, throughfall and other specialised variables. A further development of the logger—in fact a simplification of it—is the Event Recorder.

As its name indicates this does not record analogue signals such as those of an AWS. but events, such as the tip of a raingauge bucket, or the rotation of a shaft. Some 20 sites are now instrumented with these recorders linked to 'Rimco' raingauges; they are being used for an intensive study of the effects of slope, altitude and aspect on rainfall. The recorder's cassettes have the advantage that they too can be read on the same common reader as is used for AWS, water level, etc.

A development of the logging system is a unit which can be plugged into an AWS or level station, allowing it to telemeter its data. This unit stores the most recent 256 words recorded by the logger. It employs a solid state store and in no way affects the logger's cassette record. This store can be interrogated over a telephone link via a GPO modem and the received data, transmitted in ASCII code, are listed on teletype. The equipment has reached a stage of development where the GPO has approved the design; the prototype has been tested at the Institute over the internal telephone network and also tested from −30°C to +50°C. The installation of a modem at the Plynlimon office is complete and AWS data are now regularly received at Wallingford. These data are processed by a microprocessor to give listings of the seven variables.

New methods in logging

The Microdata logging system is expected to be a viable system for about 10 years; during this period it will be necessary to develop its successor. A specification has now been written for this, based on the way it seems technology will develop in the next few years. Since the new system will replace the old, there is merit in there being some compatibility, where practical, between the two. The way in which the new will differ most markedly from the old is in its ability to use solid state stores as well as, and perhaps eventually in place of, magnetic tape, as the recording medium. At present such stores are of relatively low capacity, but they are already big enough to be of use and they are expected to improve. Telemetry will also be a more integral feature of the new system, made practical through the ease with which solid state stores can be interrogated remotely, unlike magnetic tape records.

Design and development of systems using solid state logging have begun at the Institute. The first used a shift register to record daily rain totals for a period of 32 days. It has now been superseded by a system using RAMS (random access memories). Unlike the former this can be interrogated on site, using a portable display unit, and its contents displayed for any one day in any order; further the contents of the store are not lost by the action of interrogation. Development is at present centred around enabling the RAM to be returned to base, connected to a micro-processor and its contents listed on a teletype in real units—an obvious advantage to a user lacking a computer.

The third instrument, just on the point of field test, uses RAMS in a multi-input system. This monitors solar and net radiation, wet bulb depression, air temperature, wind run and rainfall. Eight days of three-hourly means and totals can be stored, the means being obtained digitally in an interface unit prior to storage.

Pressure transducer tensiometers

Manually-read tensiometers with mercury manometers or Bourdon-type gauges as pressure indicators have been in use for many years. For certain applications they have many disadvantages: they are unsuitable for automatic registration of data, they cannot be used for measurements below about 3 m depth without digging large and costly pits and they react rather slowly, which precludes their use for observing events happening on time scales of less than a few hours.

Pressure transducers, with low volume displacement for a given pressure change, are now available as moderately priced, accurate and reliable units of small size and low power consumption and can overcome most of the problems detailed above. Several different designs of tensiometer using pressure trans-

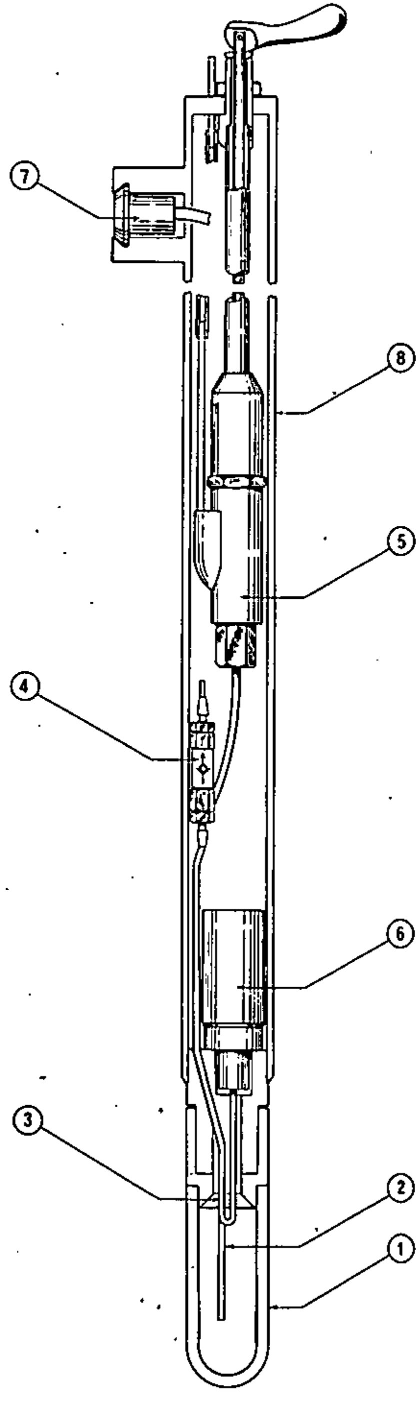


Figure 32. *Diagram of prototype purgeable recording tensiometer showing (1) Porous ceramic cup; (2) Purging tube—inlet; (3) Purging tube—outlet; (4) One-way valve on outlet; (5) Remotely-operated valve on inlet; (6) Pressure transducer +5 psi to −15 psi; (7) Transducer socket connection: can be read automatically or manually with 9v power supply and voltmeter; (8) 1 inch OD stainless steel case tailored to required installation depth from a minimum of 35 cm overall to 2 m or more*

ducers are cited in the literature but none have appeared so far which allow *in situ* purging of the units. In many field situations, particularly within the topmost metre of soil, frequent purging is necessary.

Such a fast-response, purgeable recording tensiometer has been under trial for two years but not without a measure of both mechanical and electrical problems. However, the results obtained demonstrate the potential value of the instrument and a new design was prepared and built incorporating a more robust transducer. The production prototype of this new design (see Figure 32) has proved stable and reliable under test conditions and is now undergoing field trials.

For situations when tensions remain lower than about 400 cm water or for use over short time periods, a cheaper alternative is to use simple non-purgeable transducer tensiometers. Accordingly, a non-purgeable design has been produced and a set of ten of these tensiometers installed for a trial period. A further instrument has been installed at 7 m below ground level in a 12 cm borehole in the chalk at Feltwell (see page 44) using a specially designed screw operated scissor jack to press the porous pot horizontally against the unlined borehole wall. First results are very promising and two more devices are being made to monitor tension gradients close to the water table.

The output from any of these tensiometers can be measured directly with a portable DVM or can be recorded on a standard Microdata logger fitted with appropriate interface units giving a resolution of $\pm 2{\cdot}5$ cm water tension over the whole working range (0 to $\sim$800 cm).

The autoprobe

This is an automated soil moisture measuring system. A modified neutron probe is moved automatically up and down an access tube, stopping at pre-set depths to measure and record the moisture content of the soil. The probe is moved by compressed air and the data are stored on a modified Microdata logger.

Several advances have been made over the year, notably in two areas. The control system has been further developed to increase the accuracy in positioning the probe; its position can be repeated to ± 1 cm without any subsequent drifting. The new control system is also more compact and has a reduced power requirement. The probe's pulses are transmitted to the surface by an infra-red optical link, considerably improved to reduce the dead time. The pulses are only about 1 microsecond; compared with the first prototype with a pulse width after transmission over the optical link of the order of 30–40 μ sec, in the later versions this has been reduced to 3–4 μ sec.

Computer Services

Computer installations

The Univac 1108 has now been in use for 2 years and undertakes all the Institute's data processing. It is at present manned during office hours only, but is left running at other times when it can be accessed by terminal users. Total usage is over 30 hours per week, of which approximately a quarter is used by other NERC institutes, principally the Experimental Cartography Unit, the Institute of Geological Sciences and the Institute for Marine Environmental Research. Over 1100 runs are processed each week, of which half are submitted from demand terminals. The batch runs, however, account for three-quarters of the computing time used.

A terminal has been installed in the Institute's Plynlimon office, connected to Wallingford by a leased telephone line which can be used for speech or data communications. ECU and IGS have installed at their offices in South Kensington terminal concentrators which they use to submit work over a common leased line to the computer.

The experiment of unmanned running, started in February, has proved very successful; it has provided terminal users access to the computer when it is lightly loaded thus giving rapid response. In addition it has been possible to clear much of the batch work left at the end of each day and to run certain large 'number-crunching' jobs overnight, providing a fast turn-round for these jobs without affecting other users.

Software is being developed to connect the Univac to the SRC/NERC network based on the Atlas Laboratory, Chilton. When this network is complete, NERC institutes will be able to submit work to the Univac at Wallingford or to the ICL 1906A and IBM 360/195 computers at Chilton, depending upon the requirements of their job.

Several software packages have been mounted on the Univac. These include routines for graph-plotting and display terminals, contouring programs and programs for statistical analysis. Applications work is currently centred on developing the CAPTAIN package. This will be an interactive package concerned with the modelling of discrete-time, single input-single output systems (eg, rainfall-runoff systems), and will have extensive graphics facilities.

The DMS-1100 data base management system is being installed to handle the data collected from experimental catchments. This should provide a simple way of associating experimental measurements with the instrument site and the catchment where they were made. This management system will also be used by ECU.

The PDP8 computer is now used mainly for translating cassettes from automatic weather stations and other data loggers. A second PDP8 is being purchased to provide extra capacity to handle the large number of cassettes now being used. The PDP8 system also provides additional input-output facilities; its paper tape reader provides a further input channel to the Univac, whilst its lineprinter can be used to offload output or as a backup.

A fast Calcomp 936 plotter is installed. It is heavily used for plotting hydrographs, contour maps and borehole logs. In addition, plotting services have been provided to SRC laboratories.

Data processing programs

The ever-increasing amount of data being collected on the Institute's magnetic tape logging system calls for sophisticated data handling techniques if the information is to be readily available for analysis. Methods are being developed by which the logged data are scanned by the computer to detect timing and sensor errors ('quality control'); these, if found, are corrected either manually or, in some simple cases, by the computer, before the clear data are assembled in an easily-accessible data store and are used to calculate the quantities required for water balance calculation and modelling. The data are labelled with quality codes and any gaps are bridged wherever possible to produce hourly and longer period averages and totals. The Penman-Monteith equation is now used to give hourly and longer period totals of evaporation for various surfaces. Quality control and calculation procedures have also been developed to deal with other logged data, as for example, from level recorders.

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Beardsell, M.F., Jarvis, P.G. and Davidson, B. 1972. A null balance diffusion porometer suitable for use with leaves of many shapes. *J. Appl. Ecol.,* 677–690.

Beran, M. 1975. The extension of short records. *ICE, Flood Studies Conf., London, 1975*, 53–56.
Various techniques for augmenting information contained in short records for flood design purposes are discussed, a classification scheme based on details of the techniques proposed, and comments made on the suitability of different techniques for different design circumstances. An extension technique should be chosen in which the hydrological factor of the design is explicity incorporated.

Blyth, K. and Kidd, C.H.R. 1976. The development of a meter for the measurement of discharge through a road gully. *(In press.)*

Calder, I.R. and Rosier, P.T.W. 1976. The design of large plastic-sheet net rainfall gauges. *J. Hydrol., 30.*
A novel design of gauge for measuring net rainfall beneath a forest canopy is described. The advantages of this system, based on the use of a large plastic sheet, over conventional throughfall and stemflow measuring systems are discussed.

Calder, I.R. 1976. The measurement of water losses from a forested area using a 'natural' lysimeter. *J. Hydrol., 31.*
Water losses due to transpiration and evaporation of intercepted water were measured using a 'natural' lysimeter, and compared with estimates of potential evaporation from meteorological observations. Given certain assumptions concerning the forest canopy, the the lysimeter observations were used to estimate runoff

from the experimental catchment of the Upper Severn, within which the lysimeter is sited; this estimate agreed well with observation.

Clarke, R.T. 1974. The representation of a short period of experimental catchment data by a linear stochastic difference equation. *Symp. on Mathematical Models in Hydrology, IASH/UNESCO, Warsaw, 1971*, 3–15.
The use and value of stochastic models for short term hydrological forecasting is discussed; in particular, one such model is fitted to a short period of record from a densely-instrumented experimental catchment.

Clarke, R.T., Leese, M.N. and Newson, A.J. 1975. Analysis of data from Plynlimon raingauge networks: April 1971–March 1973. *Inst. Hydrol., Wallingford. Rep. 27.*
The characteristics and variability of monthly rainfall data from the Wye and Severn catchments over a 2-year period are discussed. An investigation of domain theory is undertaken, and used when estimating mean areal rainfall. Hourly rainfall is also described, and details given of the raingauge network used.

Cole, J.A., McKerchar, A.I. and Moore, R.J. 1975. An on-line forecasting system incorporating radar measurement of rainfall as used to assist the short-term regulation of the River Dee in North Wales. *Symp. on Application of Mathematical Models in Hydrology and Water Resources. Bratislava, 1975. IAHS publication 115.*
A real time system of flow forecasting has been implemented for river regulation and flood warning purposes for the River Dee, North Wales. Using on-line telemetry of radar-based rainfall and of other hydrometric data, flow forecasts are achieved by a combination of rainfall forecasts and rainfall-runoff and channel routing models. Reservoir control policies are outlined.

Cunnane, C. 1975. Flood estimation by statistical methods. *ICE, Flood Studies Conf., London, 1975*, 43–46.
Following a general history and outline of statistical

methods used in flood estimation, several different applications are discussed and recommendations made. Approximate formulae for the standard errors of flood estimates are given, and a scheme for estimating the T-year flood presented.

Cunnane, C. and Nash, J.E. 1974. Bayesian estimation of frequency of hydrological events. *Symp. on Mathematical Models in Hydrology, IAHS/UNESCO, Warsaw, 1971*, 47–55.

A distinction is drawn between a sampling confidence interval and a probabilistic statement concerning the value of a population parameter. A method is developed which uses Bayes' theorem to combine the information of a regional flood frequency analysis and that of a sample of annual maxima to obtain a posterior probability distribution for a flood corresponding to a given return period.

Cooper, J.D. 1974. Etude de flux vertical non saturé à Thetford Chase (Norfolk). *Bull. du B.R.G.M., (2), III, 2*, 171–174.

A station was set up for tensiometric measurements and measurements of water content to study the use of soil water by trees in Thetford Forest. The estimation of the flux of soil water was attempted without having to fall back on the use of tensiometers.

Douglas, J.R. 1974. Conceptual modelling in hydrology. *Inst. Hydrol., Wallingford. Rep. 24.*

A programming package developed to assist the system modeller examine and improve the performance of his model is described. Details are given of a specific model developed at the Institute to predict the flow hydrograph for their own research catchments, and suggestions made for its future use in solving various hydrological problems.

Farquharson, F.A.K., Lowing, M.J. and Sutcliffe, J.V. 1975. Some aspects of design flood estimation. *Symp. on Inspection, Operation and Improvement of Existing Dams, BNCOLD/University of Newcastle upon Tyne.*

This paper draws on the experience gained recently from a number of studies made on behalf of consulting

engineers and water authorities by Institute staff in giving further illustration of the techniques described in the Flood Studies Report. The problems of designing against a specified return period for outflow peak are discussed; the use of local data to modify predictions from regression equations is also demonstrated. A further regression equation is presented which enables a preliminary rough estimate of the maximum hydrograph peak to be made directly in terms of catchment characteristics derived from maps.

Gay, L.W. and Stewart, J.B. 1974. Energy balance studies in coniferous forests. *Inst. Hydrol., Wallingford. Rep. 23.*

This report considers the micro-environmental factors involved when radiation is transformed into other forms of energy at the surface of the earth, with particular reference to the experience gained in two studies of the role of forest vegetation.

Gash, J.H.C. and Stewart, J.B. 1975. The average surface resistance of a pine forest derived from Bowen ratio measurements. *Bound. Lay. Meteorol., 8,* 453–464.

The methods used to measure vertical profiles of temperature and humidity above a pine forest are discussed and an objective method of calculating the Bowen ratio described. The surface resistance was computed from the Bowen ratio results and conclusions are drawn.

Gilman, K. 1975. Application of a residence time model to dilution gauging with particular reference to the problem of changing discharge. *Int. Ass. sci. Hydrol. Bull. 20(4),* 523–537.

The model is based on the residence time of fluid elements in the gauging reach; digital simulation shows that the systematic error caused by changing discharge is greatest at the start of storm runoff.

Gustard, A. and Beran, M.A. A study into the low flow characterstics of British rivers. 1975. *Symp. on Meteorological and Hydrological Aspects of Continental Drought, 16th General Assembly IUGG, Grenoble.*

The objective of the study is to produce a manual for

predicting low flows in rivers which have little or no flow data. The study is modelled on the recently completed work of the UK Flood Studies Team and will use similar data handling and analytical techniques.

Helliwell, P.R., Kidd, C.H.R. and Lowing, M.J. 1976. Estimation of the above ground runoff hydrograph for storm sewer design purposes. *National Symposium on Urban Hydrology and Sediment Control. Lexington, Kentucky. (In press.)*

Holdsworth, P.M. 1974. Application of neutron probe techniques to irrigation research and management in Jamaica. *Inst. Hydrol., Wallingford. Rep. 22.*
This report describes an Institute project in Jamaica, the main objective of which was to demonstrate the application of neturon probe techniques to the improvement of the efficiency of irrigation of bananas and sugar cane. The information gained made it possible to suggest improvements in existing irrigation schemes and recommend lines of future research.

Jones, R.C. 1975. Assessment of records and use of historic flood records. *ICE, Flood Studies Conf., London, 1975,* 39–42.
The assessment of flood records is described through the separate appraisals of the gauging station, the rating and the chart record, resulting in a simple station grading. Data extracted from chart records may be augmented by historic data to reduce the sampling error of short record statistical analyses.

Kidd, C.H.R. 1976. A non-linear urban runoff model. *Inst. Hydrol., Wallingford. Rep. 31.*
From an investigation of the above-ground phase of the urban runoff process within two small urban catchments, a lumped parameter non-linear model is postulated and compared with two simpler models (linear and time-of-entry).

Lowing, M.J. 1975. Prediction of the runoff hydrograph for a design storm. *ICE Flood Studies Conf., London, 1975,* 23–26.
This paper concentrates on the estimation of a

maximum design flood hydrogragh. Earlier methods of estimation are reviewed and recent trends discussed.

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

McKerchar, A.I. 1976. Subcatchment modelling for Dee River forecasting. *Inst. Hydrol., Wallingford. Rep. 29.*
A simple model to forecast outflows from five River Dee subcatchments has been calibrated and tested. In the model a catchment is considered as a storage and the outflow from the catchment has a logarithmic relationship with the contents of the storage.

McNeil, D.D. and Shuttleworth, W.J. 1975. Comparative measurements of the energy fluxes over a pine forest. *Bound. Lay. Meteorol., 9,* 297–313.
Simultaneous heat flux measurements were made over a pine forest in three different ways during the summer of 1974. The results obtained are considered and recommendations made on future experimental work in forest micrometeorology.

Miller, J.B. and Newson, M.D. 1975. Flood estimation from catchment characteristics. *ICE Flood Studies Conf., London, 1975,* 57–60.
A method is presented for estimating the mean annual flood for catchments without flow data by means of a multiple linear regression of mean annual flood on catchment characteristics. The predicted mean annual flood may be used with regional growth curves to provide preliminary estimates of floods of any return period.

Neal, C. and Truesdale, V.W. 1976. Sorption of iodate and iodide by riverine sediments, its implications to dilution gauging and hydrochemistry of iodine. *(In press.)*

Newson, A.J. and Clarke, R.T. 1976. Comparison of

the catch of ground-level and canopy-level rain-gauges in the Upper Severn experimental catchment. *Met. Mag.*, *105*, 2–7.
Description and comments on the results of statistical analyses comparing the monthly catch of ground-level rain-gauges with that of canopy-level gauges in the Institute's experimental Severn catchment.

Newson, M.D. 1975. Mapwork for flood studies Part 1: Selection and derivation of indices. *Inst. Hydrol., Wallingford. Rep. 25.*
This report deals with the background to the selection of morphometric variables for the Flood Studies Report, and includes a literature review, the constraints of available maps and map scales, and the results of pilot studies performed on data from Bristol Avon catchments.

Newson, M.D. 1975. Plynlimon floods of August 5th/6th 1975. *Inst. Hydrol., Wallingford. Rep. 26.*
This report describes information gained during the severe storm event centred over the Institute's experimental catchments in mid-Wales during the summer of 1973. Subsequent effects of the flood are hypothesized and discussed.

Newson, M.D. 1976. The physiography, deposits and vegetation of the Plynlimon catchments. *Inst. Hydrol., Wallingford. Rep. 30.*
An introductory background to the hydrological data of Plynlimon, based not only on the author's own work but also on the published and unpublished results of others.

Oliver, H.R. 1971. Wind profiles in and above a forest canopy. *Quart. J.R.Met. Soc.*, *97*, 548–553.
Using an on-line computer, measurements were made of wind speeds in and above a pine forest together with accurate potential temperature profiles over a wide range of stability conditions. The results are discussed, and a preliminary experiment to determine the effect of the anemometer tower structure upon wind speed readings is also discussed.

Oliver, H.R. 1973. Smoke trails in a pine forest. *Weather, 28,* 345–347.
Smoke trails were used to investigate the air flow within a pine forest to expose the short-term horizontal and vertical motions which must exist. Details of observations are given.

Oliver, H.R. 1947A. The gales of 2 April 1973. *Weather, 29,* 196–197.
This short note describes the wind measurements taken at the Institute's site in Thetford Forest during the gales of April 1973.

Oliver, H.R. 1974B. Wind-speed modification by a very rough surface. *Met. Mag., 103 (1222),* 141–145.
Wind speeds were measured over Thetford Forest with a standard anemograph and sensitive anemometers on three very windy days. From the anemograph traces it was possible to obtain values for average speeds and maximum gusts reduced to the standard meteorological height of 10 m above the 'surface'.

Oliver, H.R. 1975A. Wind speeds within the trunk space of a pine forest. *Quart. J.R.Met. Soc., 101,* 167–168.
A note on why the Institute's Thetford site is more nearly perfectly suited to the measurement of the shapes of wind profile within forests than most other sites.

Oliver, H.R. 1975. Ventilation in a forest. *Agric. Meteorol., 14,* 347–355.
A description of wind speed measurements at Thetford using sensitive photoelectric cup anemometers in conjunction with a computer controlled data acquisition system. Findings are discussed and consequences for forestry and agrometeorology considered.

Oliver, H.R. and Mayhead, G.J. 1974. Wind measurements in a pine forest during a destructive gale. *Forestry, XLVII (2),* 185–194.
A more detailed study of wind measurements in Thetford Forest during the gale of 2nd April 1973.

Oliver, S.A. and Oliver, H.R. 1973. A computer method for automatic acquisition of wind speed data. *Journal of Physics, E6*, 401–403.
A report on the way in which pulse generating anemometers have been incorporated into a computer controlled data acquisition system for taking meteorological measurements at the Thetford site.

Painter, R.B., Blyth, K., Mosedale, J.C. and Kelly, M. 1974. The effect of afforestation on erosion processes and sediment yield. *Symp. on Effects of Man on the Interface of the Hydrological Cycle with the Physical Environment. IAHS/UNESCO/WMO, Paris 1974*, 62–68.
This paper describes how the effect of coniferous afforestation on erosion processes and sediment yield in upland areas is being studied in three different experimental basins.

Richards, D. 1975. The effects of reducing raingauge network density on goodness of conceptual model fit and prediction. *Inst. Hydrol., Wallingford. Rep. 28.*
Reducing the density of the raingauge network has been shown to have very little effect on the efficiency of the three-store model used by the Institute to simulate hydrological response in some experimental catchments.

Roberts, J.M. 1976. An examination of the quantity of water stored in mature *Pinus sylvestris* L. trees. *J. Exp. Bot. (In press.)*

Roberts, J. and Wareing, P.F. 1975. An examination of the differences in dry matter production by some progenies of *Pinus sylvestris* L. *Ann. Bot., 39*, 311–324.
A study of the variation in growth rate between several selected progenies of Scots pine and the physiological characteristics underlying such variation, using growth analysis and direct measurement of photosynthetic rates.

Roberts, J. and Wareing, P.F. 1975. A study of the growth of four provenances of *Pinus contorta* Dougl. *Ann. Bot., 39*, 93–99.

Marked differences in height growth existed between four provenances. These differences were shown to be related to the numbers of needle initials laid down in the terminal leads of the provenances. The paper suggests that the slower growth of some provenances may be due to 'sink limitation' rather than 'source limitation' (for instance lower photosynthetic rates).

Roberts, J. 1976. A study of root distribution and growth in a *Pinus sylvestris* L. (Scots pine) plantation in East Anglia. *Plant & Soil, 44*, 607–621.
A description of the root systems in a Scots pine forest was obtained by soil coring, soil monolith and root observation trenches. The description included lateral and vertical arrangement of roots in different size classes and their seasonal growth.

Roberts, J. 1976. An examination of the quantity of water stored in mature *Pinus sylvestris* L. trees. *J. Exp. Bot. 27*, 473–479.
A technique is described which was used to measure the quantity of water stored in trees. This stored water was considered and discounted as a source of discrepancy between two estimates of evaporation.

Scholander, P.F., Hammel, H.T., Bradstreet, E.D. and Hemmingsen, E.A. 1965. Sap pressure in vascular plants. *Science, 148*, 339–446.

Shuttleworth, W.J. 1974. The temperature variation of the canopy and trunk of Scots Pine and its relation to the net input of radiation and to air temperature. *British Ecological Soc. Symp.*—Light as an Ecological Factor.
Data are presented which suggest that aerodynamic mixing in a forest plantation is sufficient to ensure that the difference between the average temperature of its exposed surfaces and air temperature is small compared to the diurnal temperature range.

Shuttleworth, W.J. 1976A. Experimental evidence for the failure of the Penman/Monteith equation in partially wet conditions. *Boundary Layer Met., 10*, 91–94.
An account of recent experimental evidence which

suggests the inapplicability of a simple planar model (of the Penman-Monteith type) as a theoretical description of evaporation from a partially wet canopy.

Shuttleworth, W.J. 1976B. A one dimensional theoretical description of the vegetation-atmosphere interaction. *Boundary Layer Met. (In press.)*

Smith, F.B., Carson, D.J. and Oliver, H.R. 1972. Mean wind-direction shear through a forest canopy. *Boundary Layer Met., 3,* 178–190.
The equations of motion applying to the wind field in a forest canopy are simplified to a balance between the shearing stress gradient and either the form-drag of the leaves in the upper dense canopy, or the overall horizontal pressure gradient in the more open space beneath. The equations imply that, in descending through the forest, the stress and wind vectors turn through an angle which depends on the forest characteristics and on the stability and the speed of the airflow above the forest.

Stewart, J.B. 1971. The albedo of a pine forest. *Quart. J.R. Met. Soc., 97,* 561–564.
The albedo of a pine forest was measured for a total of 243 hours during the summer of 1970 by pairs of Kipp solarimeters whose output was recorded by a computer controlled data acquisition system.

Stewart, J.B. and Thom, A.S. 1973. Energy budgets in pine forest. *Quart. J.R. Met. Soc., 99,* 154–170.
Hourly energy budgets measured in Thetford Forest are analysed for seven fine days in months from May to September.

Stewart, J.B. 1976A. Evaporation from the wet canopy of a pine forest. *(In press.)*

Stewart, J.B. 1976B. Effect of rain and dew deposition on measurements of net radiation. *(In press.)*

Stewart, J.B. and Oliver, S.A. 1970. Evaporation studies at Thetford, Norfolk. *13th Aberystwyth Symposium—Forest Meteorology.*
This paper describes the preliminary results from the

Institute's Thetford project, designed to compare the rates of evaporation of intercepted water and transpiration under various meteorological conditions.

Sutcliffe, J.V. 1975. Choice of estimation techniques, *ICE, Flood Studies Conf., London, 1975*, 67–69.

Two main approaches to methods of flood estimation are described briefly. The choice in different circumstances of methods of estimation is discussed, with reference to the examples given in the Flood Studies Report.

Thom, A.S. and Oliver, H.R. 1976. On Penman's equation for estimating regional evaporation. *(In press.)*

Thom, A.S., Stewart, J.B., Oliver, H.R. and Gash, J.H.C. 1975. Comparison of aerodynamic and energy budget estimates of fluxes over a pine forest. *Quart. J.R. Met. Soc., 101*, 93–105.

Values of the total vertical flux of sensible and latent heat over a level forested region, obtained from aerodynamic formulae appropriate to airflow over relatively smooth surfaces, are found to fall consistently short of independent energy-balance estimates.

Truesdale, V.W. 1975. 'Reactive' and 'unreactive' iodine in seawater—a possible indication of an organically bound iodine fraction. *Marine Chem., 3*, 111–119.

An iodine component in seawater, which is 'unreactive' to the total inorganic method described by Truesdale and Spencer (1974), has been discovered. The component is measured as the increase in 'reactive' iodine that accompanies irradiation of seawater with high-intensity UV light. As some known organic-iodine compounds behave in a similar manner to UV radiation, it is suggested that the 'unreactive' iodine is organically-bound iodine.

Truesdale, V.W. and Smith, C.J. 1975. The formation of molybdosilicic acids from mixed solutions of molybdate and silicate. *Analyst, 100*, 203–212.

A fundamental re-appraisal of the conditions leading to the formation of α- and β-molybdosilicic acids has been made and the rate of formation of each compound at various known pH and molybdate concentrations is discussed. A number of hitherto unexplained complications reported by other workers are now resolved.

Truesdale, V.W. and Smith, C.J. 1975. The spectrophotometric characteristics of aqueous solutions of α and β molybdosilicic acids. *Analyst, 100,* 797–805.
The spectrophotometric properties of α- and β-molybdosilicic acids have been studied under various conditions from which it appears that the molybdosilicic acids form charge-transfer or other complexes with molybdate species in solution. The implications of these findings, which conflict with the results obtained by most previous workers, are discussed.

Truesdale, V.W. and Smith, P.J. 1975. The automatic determination of iodide or iodate in solution by catalytic spectrophotometry, with particular reference to river water. *Analyst, 100,* 111–123.
A catalytic procedure using a Technicon AutoAnalyzer (I) for determining iodide or iodate added to river water during dilution gauging is described. The shape of the most appropriate calibration graph is considered, together with the effects of changes in temperature, reaction period and spectrophotometric variables.

Truesdale, V.W. and Chapman, P. 1976. Optimisation of a catalytic procedure for the determination of total iodine in seawater. *Marine Chem. 4,* 29.
A precise method for the determination of total iodine in seawater is described, together with ways in which the procedure can be varied to suit other applications.

Truesdale, V.W. and Smith, C. J. 1976. The automatic determination of silicate dissolved in natural fresh water by means of procedures involving the use of either α or β-molybdosilicic acid. *Analyst, 101,* 19–31.
The practical application of Truesdale and Smith's (1975) fundamental re-appraisal of the conditions

that lead to the formation of α- and β-molybdosilicic acid in aqueous solution is described. Tests of the precision of the two procedures proposed were carried out on samples of natural water from upland Wales.

Staff of the Institute of Hydrology

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A.N.Mandeville PhD *Rainfall-runoff modelling*
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G.L.Miles *Instrument craftsman*
M.R.Stroud *Automatic weather station technician*

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Mrs A.J.Newson BSc *Flume calibration; spatial variability in rainfall*
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Programme of Research 1976 List of ongoing projects as at 1 April 1976

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

Research area II – hydrological processes

L Development, testing and use of evaporation detection apparatus
Physical controls of evaporation
Biological controls of evaporation
C Interception studies
Fog drip
C Soil moisture fluxes in the unsaturated zone
Soil physical controls of runoff from first-order basins
Tritium studies
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

Research area III – applied hydrology

R Water resources of Tehran basin
R Pilot study, catchment experiment in Kenya
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

Service activities

Lysimeter studies
Development of standard neutron probe and autoprobe
Development of automatic soil station and tensiometers

FLOOD STUDIES REPORT

IN FIVE VOLUMES

published by:

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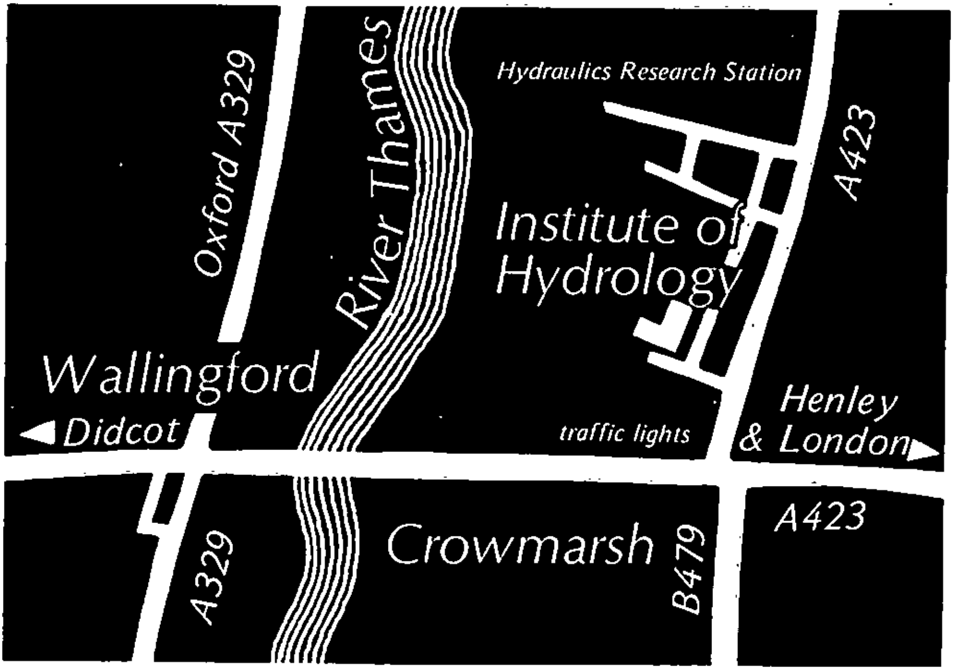
1975

The Flood Studies Report provides a variety of methods by which the magnitude and frequency of floods may be estimated, either at a site with flow records or at an ungauged site, and discusses the circumstances in which a particular method of estimation is suitable.

The investigations and analysis on which the recommendations are based are described, and sufficient statistical and hydrological theory is presented to provide a comprehensive guide to the hydrological, meteorological, and hydraulic aspects of flood estimation.

The Report is available at a price of £40 for the complete set of five volumes in a slip case, including packing and postage within the British Isles. (Equivalent rates are £43 for Europe and £45 for the rest of the world.) An additional set of unfolded maps, for Drawing Office use, will be supplied at a cost of £10.

For those concerned with rainfall estimates but not with river flows, Volume II (Meteorological Studies) and related maps is available separately at a cost of £15. Orders, including remittance, should be sent to the Director, Institute of Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxon OX10 8BB. Cheques should be made payable to the Natural Environment Research Council.



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