INSTITUTE of HYDROLOGY

LOCAL CALIBRATION OF RAIN RADAR AND THE DEVELOPMENT OF FLOOD FORECASTING MODELS: OUTLINE PROJECT PROPOSAL FOR ANGLIAN WATER

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Institute of Hydrology

April 1987

1. INTRODUCTION

This document presents an outline proposal for a project to develop systems for the local calibration of weather radar and for flood forecasting for use by Anglian Water. The outline proposal has been prepared along the lines of a project brief prepared by Anglian Water and included as Annex I of this report. This brief proposes that the project be comprised of a "Preliminary Design Study" lasting for 3 months followed by a "Main Project" which would be completed over a three year period. Consequently, the proposal for the Main Project as presented in this document serves only as a preliminary outline of what might be done. It would be the aim of the Preliminary Design Study to firm up these ideas through extensive discussions with Anglian Water and Logica personnel, and to modify them where necessary.

The outline proposal for the second stage is presented in the next section. This is followed by a section on technology transfer which outlines how expertise and software will be disseminated to Anglian personnel through selected case studies and an extensive training programme. A section on computing outlines the computer hardware and software that IH has at its disposal to assist in carrying out the project, and highlights the experience gained using DEC equipment for real-time data acquisition and modelling applications. The project team to be involved in carrying out the work is presented next, and curriculum vitae of the individuals concerned are included as Annex III. Finally a provisional indication of the time schedule and costing of the proposal is presented.

2. OUTLINE PROPOSAL

2.1 General

The overall project would be addressed on three broad fronts:

a) calibration of weather radar using local telemetering raingauges,
b) development of techniques for flood warning, both model-based and monitor-triggered,

and c) development of a decision support system for flood warning.

Development of the decision support system would serve to bring together the products developed and evaluated under (a) and (b) to form a facility to assist decision-making during flood events. The system would be capable of providing a range of information derived from:

a) raingauge or weather radar data in grid square or basin average form;

b) rainfall-runoff models and channel flow routing models appropriate to the hydrological conditions, and incorporating updating techniques;

and c) monitor-triggered warning procedures based on raingauge and/or weather radar data.

The decision support system would be menu-and-form driven and make extensive use of colour graphics displays to communicate information in a readily comprehended manner.

2.2 Calibration of weather radar

Existing weather radar systems within the UK employ a small number of telemetry raingauges (usually five) for the purposes of calibration. However, Anglian Water in common with other water authorities have a much greater number of telemetry raingauges available which could be employed to improve upon this basic calibration. The level of improvement would be expected to be particularly good for the Chenies weather radar, currently employed by Anglian, which uses only calibrating raingauges outside the Anglian region. Basic research is required using space-time correlation techniques to analyse raingauge and radar measured rainfall fields for a range of synoptic conditions to develop appropriate local calibration procedures. This is an area of current research under IH's research programme on "Real-time forecasting of river flows" commissioned by MAFF. The Anglian project would draw upon the results of this work, thereby avoiding the need for the authority to fund basic research directly.

Even with the implementation of the Anglian radar to complement the existing Chenies radar within the project time span, much of the Anglian region will lie outside the 75 km range generally considered to provide quantitatively useful data (Figure 1). Special consideration would therefore be given to the problem of calibration at long range. Orographic effects on the calibration would appear on a priori grounds to be less important for Anglian than other regions of the UK and may require less attention.

Special attention will also need to be given to the possible use of the 12 telemetering raingauges located on the roofs of flow measuring huts in the Colchester Division area. The less accurate data obtained on account of their non-standard exposure may have to be borne in mind if they are to be used for radar calibration. Assessing the merit of a particular calibration procedure in terms of the resulting improvement in flood forecasting performance will ensure that a useful calibration is obtained.

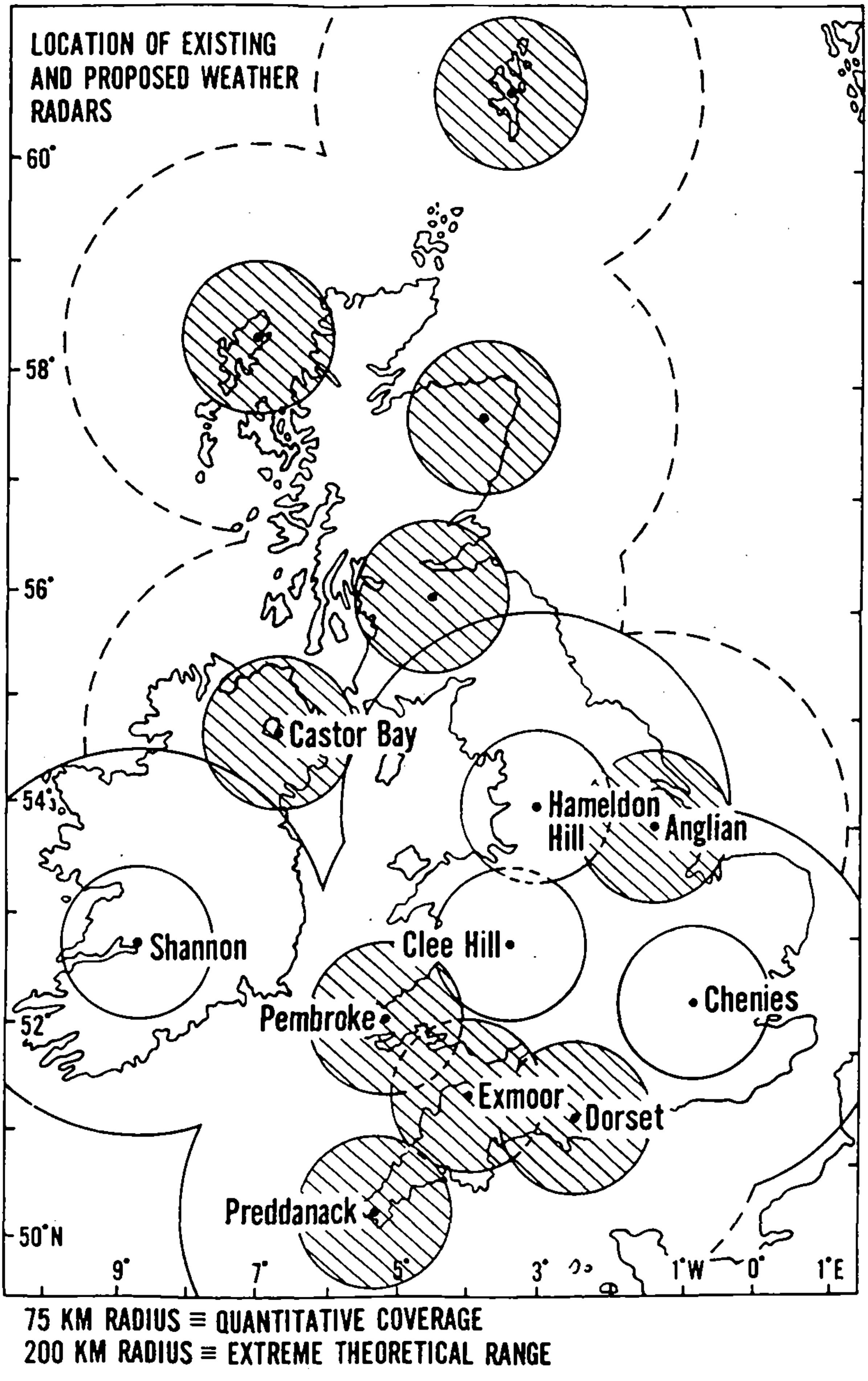

Figure 1 Location and range of existing and proposed weather radar in the UK

The project would also extend to consider the inclusion of new radar products, notably FRONTIERS, into the system for flood warning. Dependence of flood forecasts on reliable rainfall forecasts for lead times beyond the natural response time of a catchment make rainfall forecasting particularly important. Current research at IH on space-time correlations of rainfall using weather radar and local raingauges may lead to local rainfall forecasting procedures being available to complement the lower resolution FRONTIERS product.

2.3 Flood warning procedures

Two types of flood warning procedure will be considered within the project. The first will be based on a modelling approach aimed at forecasting flows using rainfall-runoff and/or channel flow routing models. This procedure will include the facility to incorporate current measurements of flow through an updating procedure to improve the forecast's precision. The second flood warning procedure will be based on the development of a simple trigger alarm system that employs monitored data derived from raingauge and/or weather radar. Instantaneous and/or cumulative rainfall totals will be related to the risk of flooding at flood prone sites. Selection of either type of procedure, or both, will depend on local circumstances and experience gained in their application within the project period.

A modelling system would be developed as part of the project having a modular structure which would accommodate a range of rainfall-runoff and channel flow routing models. These would be comprised of models already existing within the Divisions of Anglian Water as well as those provided by IH. Simple transfer function models, non-linear storage models and conceptual models exist in the form of computer programs at IH and would be made available to the project. Also available are programs for flow routing which include (i) Muskingum-Cunge model, (ii) variable parameter diffusion model, (iii) Nash/Kalynin-Miluyokov model, (iv) simple kinematic wave model with discharge dependent wave speed (Jones and Moore, 1980), and (v) PAB (parabolic and backwater), a new unconditionally stable flood routing scheme particularly suited for real-time forecasting, developed by Todini and Bossi.

An important feature of the modelling system would be the use of a general river network structure which would allow its application to a range of river system configurations. A prototype structure algorithm has already been developed for design applications and this would be used as the starting point for developing a river network system for real-time application. Its modular structure would permit a flexible choice of rainfall-runoff and channel flow model along the river network. A system of this kind would seem to be the best way of meeting the project brief's requirement specified in Section 4.1, Annex I, aimed at meeting the forecasting needs of all Divisions of Anglian Water. The design of the system would have to bear in mind the dual requirement for an off-line calibration system as well as a real-time operational system and this may demand implementation on main frame and micro computers respectively.

It is envisaged as part of the preliminary design study that a restricted number of modelling modules would be decided upon through discussion with Anglian staff, and after an assessment has been made of current forecasting procedures in use by Anglian Water. This will ensure that a realistic target is set bearing in mind time and financial constraints on the project.

2.4 Decision support system for flood warning

The set of procedures developed for flood warning would be made available to the user in the form of a decision support system which would allow the user to access various forms of information to assist in the initiation and dissemination of a flood warning. Information on forecast flows at key points along the river system would be displayed as colour displays, as would information on cumulative rainfall totals as part of a monitor-triggered warning procedure. The system would be able to interrogate the real-time data base in a variety of ways and display them as tables and/or graphs. The microcomputer based system would be menu-and-form driven. IH has recently implemented a decision support system of this kind for Thames Water on a DEC PDP11/73, but for real-time drought management rather than for flood warning (Moore et al., 1986(a),(b), 1987).

3. TECHNOLOGY TRANSFER

Following a review of data availability as part of the Preliminary Design Study a small number of river basins representative of the range of hydrological conditions encountered within the Anglian would be selected. These would be used as case studies for model evaluation and system development. Implementation of flood warning systems for each division would be the responsibility of Anglian Water. Thorough training in the application of forecast procedures and the related software products would be given to enable divisional hydrologists to implement their own divisional flood warning systems.

4. COMPUTING

4.1 Computing hardware

The following provide a summary of the computing hardware that is at IH's disposal.

for carrying out the project.

(i) PDP-11/23 Minicomputer

IH has a new μPDP-11 running μRSX-11. The configuration of this system is:

1 μPDP-11/23 with 1.5Mb of memory, 31Mb of direct access storage provided on 1 11Mb fixed disk (RD51 winchester) and 2 10Mb RL02 removable pack drives, 1 800/1600 bpi tape drive and a small LA50 dot matrix printer.

A number of terminals are attached to this machine:

1 VT220
1 VT241 colour graphics terminal
1 VT125 monochrome graphics terminal
1 VT100
1 DECwriter IV (printing terminal)

An HP pen plotter can also be attached. File transfer facilities between the PDP-11's and the IBM 4381 are available.

(ii) IBM 4381 Mainframe

The configuration of the new NERC mainframe at Wallingford is:

1 4381 dual processor with 16Mb of memory, 15Gb of direct access storage provided on 4 2.5Gb and 1 5Gb disk drives, 4 1600/6250 bpi and 1 800/1600 bpi tape drives, 1 2000 lpm upper case only printer and 1 1600 lpm upper/lower case printer.

There are two directly connected IBM 3179 colour graphics terminals available to IH staff, one of which has a colour inkjet plotter for screen dumps. A number of HP7475 pen plotters are available as well as a Benson 3 pen drum plotter.

A Sigmex colour graphics workstation is also available having special purpose hardware for various graphics functions, 1Mb display file store, 1448 by 1024 pixel display, interactive data tablet and ink jet printer. (This supports a slight variation of the GKS standard with all primitives, segment functions and transformations implemented locally with bundled or individual attribute handling and full input support.)

(iii) I^2S graphics workstation

A new I^2S graphics workstation driven by a Microvax is to be installed at IH in August. Whilst primarily intended to support remote sensing applications it will be available for use by the project team.

(iv) VAX cluster

IH has access via the JANET network to a large VAX cluster at NERC's British Geological Survey site at Keyworth.

4.2 Computer software

Computer software exists on the PDP11/23 microcomputer and IBM 4381 main frame computer to read at-site weather radar tapes, to decalibrate the data, and to write the data in either calibrated or decalibrated form to sequentially formatted disk files ready for subsequent analysis.

Software also exists to display weather radar images in grid square form as colour coded rainfall intensity bands. The use of digital mapping techniques also allows the radar picture to be superimposed with a river network, a coastal boundary and river basin boundaries. Data can be displayed at a resolution of 2 km and/or 5 km, and as 5 minute interval "snapshots" or at aggregated time intervals chosen by the user. An example of the weather radar pictures that can be obtained from this software is shown in Figure 2.

4.3 Experience with DEC computers

Institute staff are familiar with both the RT-11 and RSX-11 operating systems. The Institute has been responsible for implementing a real-time water quality monitoring system under RT-11 and for interfacing a PDP-11 to a real-time data collection system under RSX-11. The RSX-11 system is being used for data translation involving real-time response (using interrupts) to several devices. Experience also has been gained on a PDP-11/73 system purchased by Thames Water to IH specification for both water quality and drought management modelling. A link between this machine and Thames Water's Ferranti Argus telemetry computer has been successfully established for transfer of real-time data to the models.

(a) 2 km data out to a range of 75 km

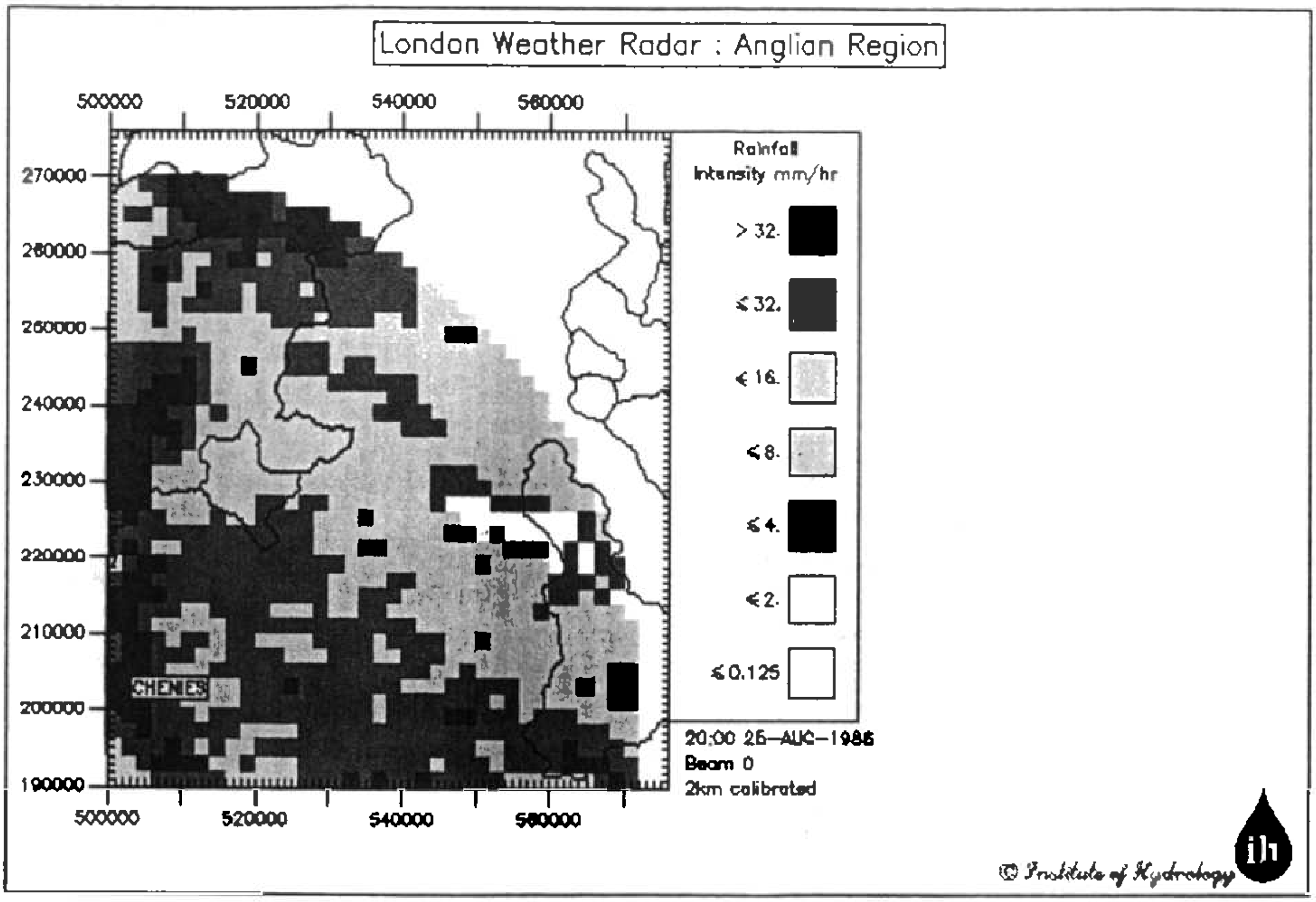

Figure 2 Weather radar displays for the Anglian region using Chenies weather radar data. The storm concerned is Hurricane Charlie which traversed the UK on 25 August 1986.

(b) 5 km data out to a range of 200 km

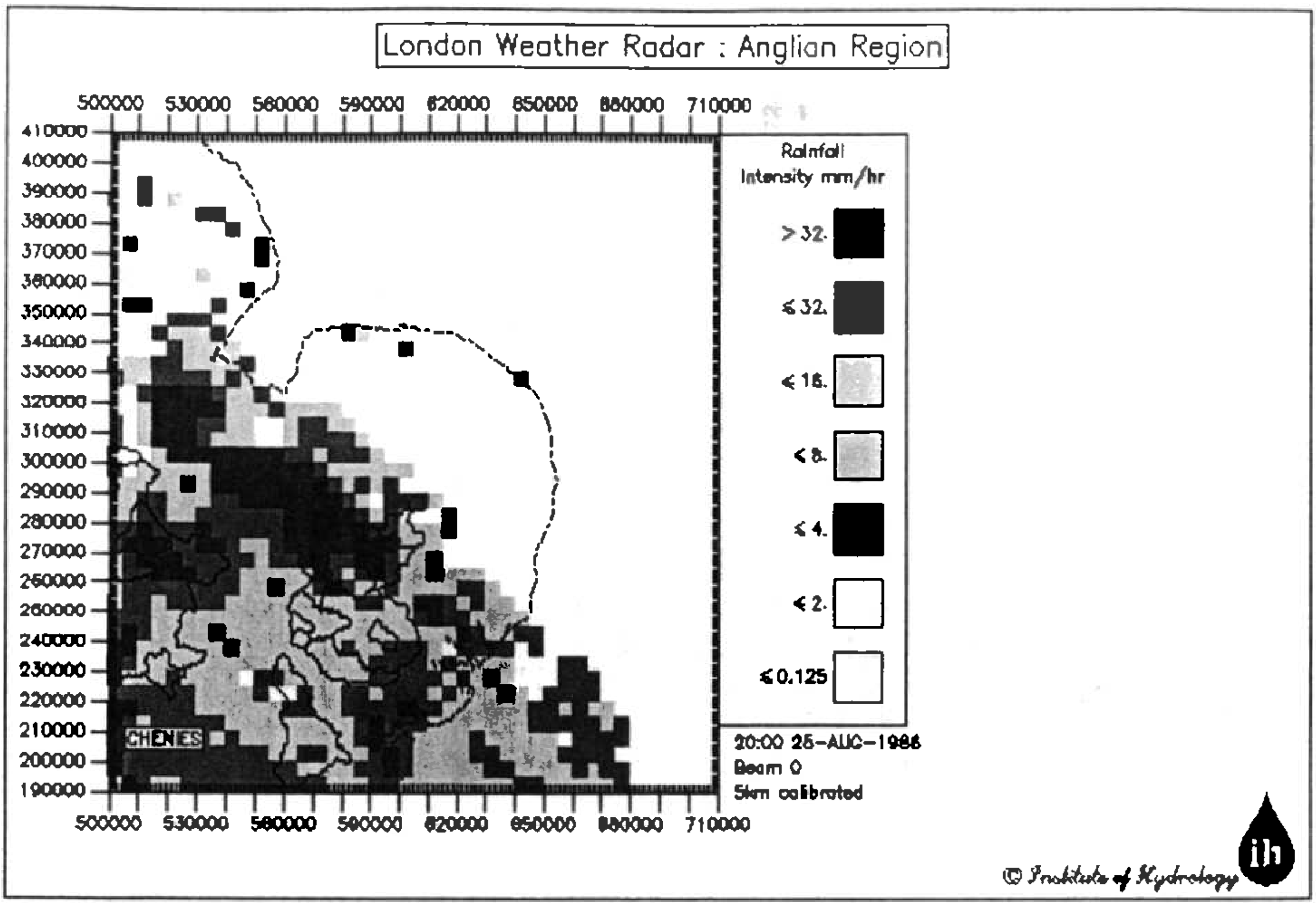

Figure 2 Weather radar displays for the Anglian region using Chenies weather radar data. The storm concerned is Hurricane Charlie which traversed the UK on 25 August 1986.

4.4 Software implementation

In the event that the configuration of minicomputer adopted for Divisional application is incompatible with the range of systems available to IH then IH could be given initial use of one of the Divisional microcomputers. Since it will be some years before the new Logica telemetry systems are fully operational in Colchester, Oundle and Lincoln divisions it might be sensible for IH to have initial use of a microcomputer allocated to one of these divisions. Such a strategy has worked well in the past when installing a water quality modelling and monitoring system for the Cambridge Division of Anglian Water on a PDP-11/23.

5. PROJECT TEAM

The IH project team that would be involved in the project are as follows:

Robert J. Moore	Project Manager
Kevin B. Black	Systems Analyst/Programmer
Bryony Watson	Meteorologist/Modeller
Jane Ridler	General support/programmer
David A. Jones	Mathematician/Statistician
John C. Packman	Urban applications
Duncan W. Reed	Flood Forecasting applications

The first three named members of the team would be primarily responsible for the execution of the project. The experience of the other members of the IH team, however, would be utilised where appropriate.

The project manager is currently responsible for the MAFF commissioned project on "Real-Time Forecasting of River Flows" and 50% of his time is currently assigned to this. This project is seen in the context of the proposal as providing the strategic research on weather radar calibration and flood modelling that would underpin the Anglian Water application. The relevance of the MAFF project to the current proposal can be seen by reference to the project summary included as Annex II. In undertaking the Anglian project it is expected that the project manager's commitment to flood forecasting research and application will increase to 70%.

Curriculum vitae for the project team are included as Appendix III of this outline proposal. These provide relevant details of the experience of IH staff in flood forecasting, weather radar, real-time data acquisition and software development. In addition three published papers which relate to work of particular relevance to this proposal are included as Appendix IV.

6. TIME SCHEDULE, COSTING, AND FUNDING

Work on the Preliminary Design Study could be started by IH as soon as a contract is agreed. A report on this study would be completed within three months of the start date of the contract. A provisional costing for this work is £5K.

At this stage it is difficult to provide a precise estimate of the cost for the Main Project. However, previous experience in developing a decision support system for drought management suggests that it would be unwise to undertake the development of a system of the flexibility required by the project brief for less than £85K. This lower estimate is based on the knowledge that basic research required to implement the project will be undertaken as part of the MAFF commission project on real-time forecasting of river flows. Emphasis will be put on better utilisation of existing flood forecasting procedures rather than development and refinement of new ones. The estimate also assumes that Logica would be responsible for the design of data structures for weather radar and telemetry data and entry and extraction of these data would be via Logica's MC16 Management Information Interface.

Annex V presents a summary of the general conditions required by NERC to be included in a formal letter of agreement with Anglian Water.

Finally, it would be prudent to consider sources of additional funds to support Anglian Water's proposed investment in weather radar and flood warning products. Within the last year a LINK research initiative has been announced aimed at providing financial support from government funds to promote collaborative programmes between the scientific community and industry. LINK provides up to 50% funding, but expects at least 50% of the funds to derive from the private sector. Whilst collaboration between a NERC institute and a water authority lies in a grey area of eligibility for funding because of a WA's public utility designation, the role of Logica within the overall project specification suggests that this tripartite project would qualify for LINK funding. The resulting software products emerging from this collaborative programme may be marketable outside the UK and would thereby be in keeping with the long-term objectives of LINK. Preliminary enquiries with the Department of Trade and Industry were received with considerable interest. As yet no programme area exists for Hydrological Applications but one could be created to accommodate an appropriate project. If advantage is to be taken of LINK then Anglian Water, Logica and the Institute of Hydrology would need to consolidate a programme of work suitable for submission to the Department of Trade and Industry. This might be considered within the Preliminary Design Study.

Figure 1 Location and range of existing and proposed weather radar in the UK

Figure 2 Weather radar displays for the Anglian region using Chenies weather radar data. The storm concerned is Hurricane Charlie which traversed the UK on 25 August 1986.

(a) 2 km data out to a range of 75 km

(b) 5 km data out to a range of 200 km

ANNEX I

ANGLIAN WATER PROJECT BRIEF

LOCAL CALIBRATION OF RAIN RADAR AND THE DEVELOPMENT OF

FLOOD FORECASTING MODELS

1. Introduction

1.1 This project will be funded by the Anglian Water Research & Development budget. It has been promoted in the name of Colchester Division but will also be of direct benefit to Oundle, Cambridge and Lincoln Divisions who plan to integrate rain radar and telemetry data. Norwich Division do not receive radar data but will benefit from the development of flood forecasting models.

1.2 A budget allocation has been made to cover the 3 years commencing 1987/88.

1.3 The project will be co-ordinated by two Divisional Hydrologists on behalf of the other Divisions, at all times maintaining close liaison with all parties involved.

2. Objectives

2.1 To develop techniques for the integration of rain radar data with Divisional telemetry systems (in conjunction with the Authority's telemetry suppliers - Logica UK Ltd).

2.2 To develop techniques to produce locally calibrated rain radar data suitable for a wide range of multifunctional uses.

2.3 To use the calibrated data in flow forecasting models which fully utilise the advantages of rain radar.

3. Background

3.1 The current situation is that Type II Chenies data (i.e. high resolution non-degraded) is received by Colchester, Oundle and Cambridge Divisions. Data is displayed and archived on Software Sciences RAU systems based on dedicated Philips P.C. microcomputers.

3.2 Oundle Division also receives degraded Network data, displayed on a dedicated Logica Vitesse microcomputer.

3.3 A limited amount of historical data has been saved by each Division for events of particular interest. All Divisions have recording raingauge data for comparison.

3.5 Lincoln and Oundle Divisions will receive data from the proposed new Lincoln radar which is expected to come on line early in 1988.

3.6 All Divisions are to have Logica telemetry systems based on DEC computers, but the configuration, communications and processing facilities will vary.

3.7 Cambridge and Norwich Divisions are well advanced, with Phase I commissioned and operational since 1986.

3.8 It will be some years before the new Logica systems are fully operational in Colchester, Oundle and Lincoln Divisions.

3.9 All Divisions have existing flood forecasting procedures of varying degrees of sophistication, ranging from station to station correlation to real-time unit hydrograph models.

4. Approach

4.1 Techniques and procedures to be developed as part of this project will necessarily have to be very flexible. It is the intention that A.W. staff will maintain a high level of involvement throughout.

4.2 The results of the project must be demonstrated on computers which are entirely compatible with those to be used in the Divisional telemetry systems. The procedures will be implemented as an integral part of the Divisional real time telemetry systems using the Logica MC16 operating system. Actual implementation will be the responsibility of each Division although the techniques should be demonstrated on a number of examples representing the range of situations throughout the Authority. Thorough training of Divisional staff is to be provided so that they can then apply the techniques to their particular requirements.

4.3 Planning of the project will depend on detailed consultation with Logica and our own Systems Engineers. For this reason it is intended to carry out the project in two stages; Firstly a preliminary design study over a three month period followed by the main project over three years.

5. Preliminary Design Study To include:

5.1 Consultation with A.W. Regional and Divisional Systems Engineers and Hydrologists and Logica U.K. Ltd. to discuss for example

(a) The type of computing facilities which will be available in each Division.

(b) How rain radar and telemetry data are to be integrated.

(c) How radar/rainfall data and flow data/forecasts are to be disseminated to remote users.

(d) The time scales of telemetry installation and the implementation of flood forecasting facilities.

(e) Current flood forecasting and warning systems.

5.2 A review of data availability (radar, recording raingauges, river flow etc.) both for the development of techniques now and for their implementation in the future. Given the three year timescale involved consideration must be given to likely developments in radar products (e.g. FRONTIERS, non-degraded network data?).

5.3 Consideration of problems in local radar calibration particular to Eastern England, e.g. the distance of many areas from a radar site, the low relief and particular climatic characteristics such as the frequency of convective rainfall.

5.4 What sort of display for calibrated data is feasible given the computing facilities and timescale, e.g. colour pictures of corrected radar data or simply subcatchment totals.

5.5 What sort of flood forecasting models would be most appropriate. (The sort of catchments to be considered will range from very small flashy catchments to large lowland rivers). They should run semi-automatically and require a minimum of interaction.

5.6 Would it be possible to automatically identify areas of heavy rain anywhere within a predefined area (e.g. A Division) and to relate these to predefined sensitive locations.

6. Main Project

6.1 The main project would consist of developing techniques to achieve realistic targets which would be mutually agreed following the preliminary design study. Our preferred approach described in 4.1 and 4.2 should be emphasised.

6.2 Close liaison between the research body and Anglian Water should be maintained and detailed interim reports will be required annually. In addition brief notes on progress will be included in Anglian Water's internal quarterly reports.

6.3 It is envisaged at this stage that the main project will be carried out as a fixed price contract, that price to be finalized after the completion of the design study.

ANNEX II

MAFF COMMISSIONED PROJECT ON REAL-TIME FORECASTING OF RIVER FLOWS: PROJECT SUMMARY

INSTITUTE OF HYDROLOGY
PROGRAMME: AB1
TITLE: Real-time forecasting of river flows
ESTIMATED COST: (1987/8) £73.6K

RESEARCH AREA: RIVER FLOOD PROTECTION
SPONSOR: MAFF COMMISSION A
CONTACT: Mr R J Moore

Background	Technical Assessment	Research Objective	Completion year	Resources for review year (per cent) 1987/8	88/9	89/90	90/1
Flow forecasts are required to provide warning of impending flooding in order to prevent loss of life and to minimise damage to property, livestock, crops, etc. Advances in real-time data acquisition systems over the last 10 years, and a reduction in their cost in real terms, has promoted the implementation of real-time systems for flood forecasting in several areas of the UK. Implementation of such systems has required research on the development of flood forecasting techniques which can be implemented in real-time on a micro-computer, and which make full use of current information on the river basin's state as provided through telemetered measurements of rainfall and river flow.	Flood forecasting practice may be advanced through research on (i) improved model structures, (ii) improved updating techniques, and (iii) improved specification of input data. Improvement in model structure has been the traditional approach to enhance forecast performance, and indeed the design of rainfall-runoff and channel flow routing models suitable for real-time implementation remains of central importance. Future research will consider their dual role as part of a river network model for flow forecasting. Techniques for updating have formed the revolutionary aspect of real-time flood forecasting systems, where the facility exists to employ current measurements of flow to improve flood forecasts. Future research will aim to develop improved adjustment schemes suitable for real-time use. Improvements to model performance through better definition of input data are to be pursued through the use of grid-square radar data, the better use of raingauge network data utilising recent advances in spatial statistics, and the use of spatial information derived from digital terrain maps.	(i) Use of weather radar data for real-time flood forecasting:					
		(a) Development of database	1987 }				
		(b) Development of simple distributed models	1988 }	55	35	-	-
		(c) Calibration of weather radar for flood forecasting	1989 }				
		(d) Assessment of weather radar data for flood forecasting relative to raingauge network data	1989 }				
		(ii) River network models for flood forecasting	1989	10	10	-	-
		(iii) Improved updating techniques		10	10	10	10
		(iv) Uncertainty of flood forecasts	1990	10	10	5	-
		(v) Snowmelt forecasting	1989	5	5	5	-
		(vi) Case studies involving implementation of computer-based flood warning systems		10	10	10	20
		(vii) New research initiatives		-	20	70	70

ANNEX III

CURRICULUM VITAE OF IH PROJECT TEAM

Curriculum Vitae

Name of firm:	Institute of Hydrology
Name of person:	Robert James MOORE
Nationality:	British
Date of birth:	20 March 1949
Profession:	Hydrologist
Position in firm:	Head of Hydrological Modelling Section
Specialisation in firm:	Hydrologist
Years with firm:	12 - permanent full-time staff member

Key Qualifications

1975 to date

Head of Hydrological Modelling Section specialising in the development of mathematical modelling techniques for hydrological and water resource applications. Specific research interests include:

* Real-time flood forecasting: Recursive state/parameter estimation algorithms for real-time flood forecasting. Identification of non-linear transfer function noise models using isolated flood event data. Raingauge network requirements for real-time flood forecasting. Real-time channel flow routing models. Member of River Dee Flood Forecasting System Project Team.
* Stochastic modelling of hydrological systems: CAPTAIN package for recursive time series modelling. Hydrological models based on the probability-distributed principle. Variance reduction techniques for stochastic water resource system risk assessment. Kalman filters applied to water quality and quantity modelling. Decision support system for drought management. Mathematical modelling of basin sediment yield. Statistical flood frequency estimation.

1984, 1985

UNESCO consultant to the National Water Plan for Portugal Project (hydrometric network evaluation; national rainfall and runoff maps; stochastic streamflow models; reservoir yield assessment).

1981, 1983

WMO consultant to the Yamuna Flood Forecasting Project, India; training seminar on flood forecasting, Bangkok, Thailand.

1974 - 1975

Water Research Centre. Modelling work for the River Dee Flood Forecasting Project and development of the CAPTAIN recursive time series analysis package.

1973 - 1975

Water Resources Board. Hydrologist in Water Data Unit concerned with maintaining a national archive of hydrological data; latterly, member of Operations Research Group engaged on water resource system simulation studies.

Education

1968	GCE 'A' levels: Geography (A), Pure Mathematics (B), Physics (B)
1971	B.Sc II(i) Geography (subsidiary subjects: Geology (2 years), Physics (1 year)), University College of Wales, Aberystwyth.
1972	M.Sc Water Resource Technology (Engineering Hydrology option), Department of Civil Engineering, University of Birmingham.

Experience

Current	Head of the Hydrological Modelling Section of the Institute of Hydrology specialising in the development of mathematical modelling techniques for hydrological and water resource applications.
1986	Decision support system for real-time drought management in the Thames basin (Thames Water).
1984 to date	Responsible for Thames Water Operational River Management Project to formulate a strategy to forecast drought and flood flows for a range of time intervals from hours to months.
1978 to date	Project Leader of MAFF Flood Protection Commission project on real-time flood forecasting.
1984 to date	Application of a rainfall-runoff-sediment model to four basins in Malawi to investigate the effect of land management practice on water and sediment yield.
1980 to date	Development of hydrological models based on the probability-distributed principle (the spatial variability of hydrological variables over a basin is described through distribution functions which are subsequently used to construct probability-distributed models of the basin response of runoff, soil moisture and sediment to rainfall).
1984 to date	Modelling of bedload movement in upland rivers.
1983 - 1985	Development of flood forecasting procedures for manual implementation in the Mahanadi River Basin, India (Overseas Development Administration).
1984 - 1985	Consultant to UNESCO on the National Water Plan for Portugal Project. To advise and assist a project team concerned with hydrometric network evaluation, synthetic streamflow models, reservoir yield assessment, and preparation of national maps of mean and percentile rainfall and runoff.
1983	Consultant to WMO to provide training on flood forecasting techniques at a WMO/UNDP Regional Training Seminar on Flood Forecasting, Bangkok, Thailand.
1982	Calibration of rainfall-runoff models using rainfall and runoff data supplemented by neutron probe derived estimates of soil moisture.
1982	Development of a supply- and transport-limited dynamic model of basin sediment yield.
1981	Development of an algorithm to calculate the derivatives of the incomplete Gamma integral, for use in gradient-based parameter estimation of models which involve convolution of the gamma density function.
1981, 1983	Consultant to WMO on the Yamuna Flood Forecasting Project, India, providing training on constrained linear system modelling, installation of programs, and application to hydrological data.

1980 - 1981	Model development work for microcomputer-based flood warning systems for Haddington, Scotland, and Market Harborough, England.
1980	Development of models of nitrification in an activated sludge plant for forecasting and control of the nitrogen content of the final effluent.
1979	Development of a simple channel flow routing model for real-time use, in which travel time varies with discharge, and forecasts are improved in real-time using a simple error predictor procedure.
1978 - 1980	Water Research Centre contract to develop and assess transfer function noise models for real-time flood forecasting application.
1977	Investigation of the raingauge network requirement for a real-time flood forecasting system using multiple input time series models.
1977	Development of a time series model relating rainfall to levels of the Dead Sea as part of a study to assess the effect of abstractions and hydropower development on Dead Sea levels (Sir Alexander Gibb and Partners).
1976 - 1979	Development and application of Kalman filter theory for recursive state/parameter estimation for use in forecasting hydrological variables. Specific developments include (i) recursive estimation of a non-linear conceptual rainfall-runoff model using an extended Kalman filter, (ii) coupled Bayesian-Kalman filter scheme for state and parameter estimation, and its application to a channel flow routing and a dynamic water quality model of dissolved oxygen and biochemical oxygen demand, (iii) state/parameter estimation of a rainfall-runoff model using statistical linearisation.
1976	Development and application of variance reduction techniques for obtaining reduced variance estimates of hydrological extremes derived by Monte Carlo simulation.
1976 to date	Statistical supervision of IH CAPTAIN recursive time series analysis package, and development of a multi-input extension.
1975 - 1976	Member of IH project team concerned with developing and implementing the River Dee Flood Forecasting System with special responsibility for the Lower Dee model and routing of tributary flows.
1974 - 1975	Water Research Centre. Responsible for the development of the CAPTAIN package for recursive time series analysis and forecasting of hydrological variables. Hydrological modelling work for the River Dee real-time flow forecasting system.
1974	Operations Research Group of the Water Resources Board. Use of synthetic flow generation models and water resource simulation models for water resource planning. Time series analysis for hydrological forecasting.
1973 - 1974	Hydrologist in Water Data Unit of the Water Resources Board with a responsibility for maintaining a national archive of hydrological data. Specific responsibility for developing stage-discharge relationships and estimates of their precision.

Publications

COLE, J.A., MOORE, R.J. (1974), 'Hydrological forecasting methods for river regulation systems'. Proc IEE Symp, 25 November, pp 4.

MOORE, R.J. (1975), 'Dee investigation simulation program for regulating integrated networks: a program documentation'. Internal Report, Water Research Centre, pp 36.

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Anon (1985), 'Flood forecasting for operational control: 1. Modelling subcatchments'. Contract report to Thames Water, Operational River Basin Management research programme, 106 pp.

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JONES, D.A., MOORE, R.J. (1985), 'Strategies for flow forecasting'. Institute of Hydrology, 32 pp.

MOORE, R.J., NEWSON, M.D. (1986), 'Production, storage and output of coarse upland sediments: natural and artificial influences as revealed by research catchment studies'. J.Geol.Soc. London, 143, 921-926.

MOORE, R.J. (1986), 'Advances in real-time flood forecasting practice'. Symposium on Flood Warning Systems, Winter meeting of the River Engineering Section, Inst. Water Engineers and Scientists, 23 pp.

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MOORE, R.J., BLACK, K.B., JONES, D.A., BONVOISIN, N. (1986), 'User guide to the real-time drought management system for the Thames Basin'. Contract report to Thames Water, Institute of Hydrology, 71 pp.

MOORE, R.J. (1987), 'Towards more effective use of radar data for flood forecasting'. In: Collinge, V.K. and Kirby, C. (eds), Weather Radar and Flood Forecasting, 223-238.

MOORE, R.J. (1987), 'Combined regional flood frequency analysis and regression on catchment characteristics by maximum likelihood estimation'. In: Singh, V.P. (ed), Flood Frequency and Risk Analysis, D. Reidel Publishing Co., 13 pp.

MOORE, R.J., JONES, D.A., BLACK, K.B. (1987), 'Risk assessment and drought management in the Thames basin'. Int. seminar on Recent Developments and Perspectives in Systems Analysis in Water Resources Management, WARREDOC Spring Meeting, Perugia, Italy, 1-3 April 1987, 16 pp.

Language Capability

	Speaking	Reading	Writing
English	Excellent	Excellent	Excellent

Signature Date

Curriculum Vitae

Name of firm:	Institute of Hydrology
Name of person:	Kevin B BLACK
Nationality:	British
Date of birth:	23 January 1962
Profession:	Computer programmer/systems analyst
Position in firm:	HSO/Computer programmer/Systems analyst
Specialisation in firm:	Computer software, hardware and consultancy
Years with firm:	6

Key Qualifications

Systems analysis :
* Responsible for design of computer based systems for Institute projects.

Software :
* Ability to program fluently in FORTRAN, BASIC and various assembly languages.
* Also experience of PASCAL and FORTH.
* Ability to design data structures and software systems.
* Able to use a number of different operating systems and understand new ones.
* Experience with DEC PDP-11, Honeywell DPS300, IBM 4381, GEC 4090, ICL and various microcomputers.

Hardware :
* Ability to understand, design and construct computer interface hardware.

Education

1978	GCE 'O' levels: Maths(C), Chemistry(B), Physics(B), Art(C), English Language(C).
	CSE: Geography(4)
1979	GCE 'AO' level: Computer Science(A).
1980	GCE 'A' levels: Computer Science(B), Maths, Chemistry, Physics.

Experience

1980	One year's work for NERC Computing Services based at the Institute of Hydrology providing advice on the use of mainframe computers and microcomputers for dedicated project work. Preliminary development of a minicomputer based Water Quality Monitoring system for Anglian Water, including data management and graphical display programs.
1981	Became a full time member of the Institute's staff (graded ASO) giving general advice to users and management on the use of computers. Further development of the Water Quality Monitoring system for Anglian Water. Interfacing of Microdata cassette translation units and solid state stores (developed by the Institute of Hydrology) to microcomputers. Development of software for the Institute of Hydrology's site in Wales (Plynlimon) to translate cassettes and stores and list the data in raw and real units, using a Commodore PET microcomputer.
1982	Development of software and hardware to interface Solid State Stores to the RML 380Z microcomputers. Development of software to control an experimental intelligent water quality monitor for Anglian Water. Development of a serial RS232 interface and terminal emulation software to allow Commodore PET microcomputers to communicate with computers on the NERC wide area network. Mounting a Water Quality model for the River Ouse and development of the 'user interface' and software for the graphical presentation of results on a PDP-11 for Anglian Water. Development of software to monitor a sensor array for an IH project in Thetford.
1983	Development of software to list Automatic Weather Station data (from Solid State Stores) on the RML 380Z and Commodore PET microcomputers and to produce Penman-Montieth evaporation estimates. Development of data handling software for an Institute project in Syria. Development of terminal emulation software for PDP-11 minicomputers.
	Development of software to convert data from discs written on the BGS Plasma laboratory facility (non standard structure) to RT-11 format so that the data can be placed on the NERC networked mainframe and mini-computers. Design and construction of a battery backed real-time clock/calendar and driving software for Anglian Water's PDP-11 minicomputer. Design and construction of Plotter interface hardware and driving software for Anglian Water's PDP-11 minicomputer. Development of software to monitor a sensor array on Commodore PET microcomputer for an Institute project in Amazonia.
1984	Promoted to SO. Development of software for a crop disease monitoring system for the Food and Agriculture Organization (FAO) for tobacco crops in Cuba and Nicaragua based on Apple look-a-like microcomputers. Mounting a Water Quality model for the River Wissey in Cambridgeshire and development of the 'user interface' and software for the graphical presentation of results on a PDP-11 for Anglian Water.

1985 Development of software to to handle Solid State Store data from microcomputers on NERC's Honeywell mainframe and the Institute of Hydrology's GEC 4090 minicomputer. Maintenance of Anglian Water's water quality experimental water quality monitor. Conversion of RT-11 menu and form filling driving software to RSX-11. Setting up of PDP-11 minicomputers at the Institute of Hydrology and the Institute's site in Wales (Plynlimon). Initial development of software on the PDP-11 to replace the Institute's PDP-8s. Conversion of river Thames flow and quality model from PDP-11 RT-11 operating system to RSX-11.

1986 Promoted to HSO. Implementation of Drought Management system on PDP-11 minicomputer for Thames Water, including the developement of a form and menu driven front end for user interaction and graphical presentation of results. Software to link the PDP-11 to Thames' real time monitoring computer so that live data can be obtained for the Drought Management system.

Extensive development of software for the replacement of the Institute of Hydrology's PDP-8 data translation computers with a PDP-11 minicomputer running the RSX-11 operating system. Menu and form filling driven programs for cassette translation, data and site management, data formatting, data editing quality control and magtape handling. Instruction of operators and users of the system. Conversion of Solid State Store software from NERC's Honeywell mainframe to the new IBM 4381 mainframe.

Development of software to produce hardcopy plots on a pen plotter for the PDP-11 based water quality model program suite.

1987 Conversion of IH's Water Flow and Quality model for the river Tamar for the South West Water Authority.

Development of a program for the graphical display of weather data for use within the Institute of Hydrology.

Publications

BLACK, K.B. inter alia (1983), "Operational Management of Water Quality in River Systems". First report to the Commission of the European Communities on Contract No ENV-400-80 UK(b) under the Environmental Research Programme.

BLACK, K.B. inter alia (1983), "Operational Management of Water Quality in River Systems". Final report to the Commission of the European Communities on Contract No ENV-400-80 UK(b) under the Environmental Research Programme.

BLACK, K.B. (1983), "Hardware Documentation for special devices on the Anglian Water Quality Monitoring system".

BLACK, K.B. inter alia (1984), "Models for Operational Control : 2 Flow and Quality Model for the River Thames".

BLACK, K.B. (1984), "User guide to the Intelligent Outstation Control Program". User guide to software written to control an experimental intelligent water quality monitor for Anglian Water from their Water Quality monitoring system.

BLACK, K.B. inter alia (1985), "Real Time Drought Management : Project Proposal to Thames Water".

BLACK, K.B. inter alia (1986), "Real Time Drought Management System for the Thames Basin". Project report to Thames Water.

BLACK, K.B. inter alia (1986), "User Guide to the Real Time Drought Management System for the Thames Basin".

BLACK, K.B. inter alia (1987), "Roadford Environmental Investigation : Tamar River Quality Model : Phase 1 report to WRc/SWWA".

BLACK, K.B. inter alia (1987), "Risk Assessment and Drought Management in the Thames Basin". International Seminar on Recent Developments and Perspectives in Systems Analysis in Water Resources Management, WARREDOC Spring Meeting, Perugia, Italy, April 1987.

Language Capability

	Speaking	Reading	Writing
English	Excellent	Excellent	Excellent

Signature Date

Curriculum Vitae

Name of firm:	Institute of Hydrology
Name of person:	David Alan JONES
Nationality:	British
Date of birth:	16 October 1951
Profession:	Statistician
Position in firm:	Senior Scientific Officer
Specialisation in firm:	Stochastic hydrology
Years with firm:	9 - permanent full-time staff member

Key Qualifications

Trained in mathematics and mathematical statistics.

Experience of application of stochastic hydrology and mathematical modelling to a range of problems.

Education

1973 Bachelor of Science (Mathematics) Honours, London.

1977 Doctor of Philosophy (Statistics), Imperial College London.

Fellow of the Royal Statistical Society.

Member of the British Hydrological Society.

Experience

1976 to date	With Institute of Hydrology:
1985	General consideration of forecasting strategies and trial of a method for long-term flow forecasting for Thames Water.
1983 - 1985	Development and application of stochastic models for fluctuations in level of Lake Victoria.
1984 - 1985	Comparison of a range of models for forecasting flows in subcatchments of the River Thames and development of a new model.
1983 - 1984	Study of rainfall records in N.E. Thailand in terms of the accuracy of estimation of areal rainfalls and the implications of this for rainfall-runoff modelling.
1983	Development of simple procedure for multi-step forecasting of seasonal input-output processes.
1982 - 1983	Development of statistical techniques for analysing non-statistical models, the parameters of which are chosen empirically to match available data.
1982	Application of a mixed stochastic dynamic programming/simulation technique for studying control rules for the Aswan High Dam formulated to meet multiple criteria.
1980 - 1981	Development of statistical techniques for selecting representative groundwater monitoring wells.
1980	Statistical analysis for rationalisation of the raingauge network in the North West Water Authority area.
1980	Development of a mixed random- and fixed-effects method for application to the relation of annual maximum floods to catchment characteristics, making direct use of separate yearly values.
1978 - 1979	Analysis of flows into the Aswan High Dam. Development of methods for assessing the fit of, and making comparisons between, already established stochastic models for the flows.
1979	Development of a simple non-linear flow-routing algorithm for real-time forecasting.
1976 - 1978	Development of methods for rationalising existing raingauge networks by calculating how well point and areal rainfalls are estimated from a given set of gauges. Application to the network in the Wessex Water Authority area.
1977 - 1978	Study of Kalman filter techniques for real-time forecasting, with applications to rainfall-runoff models and flow-routing.

1976 - 1977 Development of a simple non-linear stochastic model for simulating daily streamflow records.

Publications

JONES, D.A. (1976). 'Non-linear autoregressive processes', Ph.D thesis, University of London.

MOORE, R.J., JONES, D.A. (1977). 'An adaptive finite-difference approach to real-time channel flow routing'. In "Modelling, Identification and Control in Environmental Systems", ed. Vansteenkiste, G.C., North-Holland, pp.153-170.

O'CONNELL, P.E., BERAN, M.A., GURNEY, R.J., JONES, D.A., MOORE, R.J. (1977). 'Methods for evaluating the UK Raingauge Network', Institute of Hydrology Report No.40, pp.262.

JONES, D.A. (1978). *'Non-linear autoregressive processes'.* Proc.R.Soc.Lond.A 360, 71-95.

MOORE, R.J., JONES, D.A. (1978). 'Coupled Bayesian-Kalman filter estimation of parameters and states of a dynamic water quality model'. In "Applications of Kalman Filter to Hydrology, Hydraulics and Water Resources", ed. Chiu, C-L. Stochastic Hydraulics Program, University of Pittsburgh, USA, pp.599-635.

O'CONNELL, P.E., GURNEY, R.J., JONES, D.A., MILLER, J.B., NICHOLASS, C.A., SENIOR, M.R. (1978). 'Rationalisation of the Wessex Water Authority Raingauge Network', Institute of Hydrology Report No.51, pp.179.

JONES, D.A., GURNEY, R.J., O'CONNELL, P.E. (1979). 'Network design using optimal estimation procedures', Water Resources Research, 15(6), 1801-1812.

O'CONNELL, P.E., GURNEY, R.J., JONES, D.A., MILLER, J.B., NICHOLASS, C.A., SENIOR, M.R. (1979). 'A case study of rationalization of a raingauge network in south-west England', Water Resources Research, 15(6), 1813-1822.

JONES, D.A., O'CONNELL, P.E., TODINI, E. (1979). 'A model evaluation framework for synthetic hydrology', in "Water Resources Planning in Egypt", eds. I.M. Elassiouti and D.H. Marks, Ministry of Irrigation, Egypt, Cairo Univ/MIT Technological Planning Program.

TODINI, E., O'CONNELL, P.E. (eds) (1979). 'Hydrological simulation of Lake Nasser'. Joint IBM Italia, Institute of Hydrology Report, pp.213.

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JONES, D.A., DAVEY, J.C., HOSKING, J.R.M., O'CONNELL, P.E. (1981). An approach to the identification of representative wells for monitoring groundwater levels: Report to DOE/IGS, pp.87.

JONES, D.A. (1981). Discussion of paper by Drs. Darby and Reissland. J.Roy.Statist.Soc.A, 144(3), p.324.

TODINI, E., JONES, D.A., O'CONNELL, P.E. (1981). 'Stochastic simulation in reservoir operation - a case study'. Proc. NATO Advanced Study Institute on 'Systems Analysis and Reservoir Management', Coimbra, Portugal.

JONES, D.A. (1982). 'Various approaches to the Sensitivity Analysis of SHE: a discussion', SHE Report No.20.

JONES, D.A. (1982). 'Choice of objective functions for comparing flow forecasts', Applied Hydrology Informal Note, No.65.

JONES, D.A., O'CONNELL, P.E., TODINI, E. (1982). 'Risk evaluation of reservoir operating rules derived by dynamic programming'. Paper presented at IAHS symposium on Optimal Allocation of Water Resources, Exeter.

JONES, D.A., O'CONNELL, P.E., TODINI, E. (1982). 'Risk evaluation of stochastic dynamic programming policies using Monte Carlo simulation'. Paper presented at AGU Fall Meeting, San Francisco.

JONES, D.A. (1983). 'Statistical analysis of empirical models fitted by optimization', Biometrika 70, 67-88.

Unauthored (1983). 'A review of the hydrology of Lake Victoria and the Upper Nile'. Report for Sir Alexander Gibb & Partners.

O'CONNELL, P.E., JONES, D.A. (1983). 'An assessment of seasonal streamflow forecasting techniques', Report for WMO.

O'CONNELL, P.E., JONES, D.A. (1983). 'User manual for seasonal streamflow forecasting using the hybrid technique', Report for WMO.

Unauthored (1984). 'Notes on the further analysis of future Lake Victoria Levels', Report for Sir Alexander Gibb & Partners.

Unauthored (1984). 'Lower Mekong Basin, Water Balance Study. Phase 2 report, Part 2: rainfall analyses'. Report for ODA.

JONES, D.A. (1984). 'Statistical flood estimation methods - some possibilities for future work', Applied Hydrology Informal Note, No.95.

JONES, D.A. (1984). 'A first-principles comparison of pooling procedures for regional flood frequency curves', Applied Hydrology Informal Note, No.96.

Unauthored (1985). 'Models for operational control.
1: Rainfall-runoff models for subcatchments'. Report for Thames Water.

Unauthored (1985). 'Further Review of the Hydrology of Lake Victoria'. Report for ODA.

JONES, D.A., MOORE, R.J. (1985). 'Models for operational control. 4: Strategies for flow forecasting'. Report for Thames Water.

JONES, D.A. (1985). 'Techniques for flow forecasting. 1: Long-term forecasting using chained regressions'. Report for Thames Water.

JONES, D.A. (1985). Discussion of paper by Drs. Lawrence and Lewis. J.Roy.Statist.Soc.B, 48(2), 183-184.

Language Capability

	Speaking	Reading	Writing
English	Excellent	Excellent	Excellent

Signature   Date

Curriculum Vitae

Name of firm:	Institute of Hydrology
Name of person:	Duncan William REED
Nationality:	British
Date of birth:	19 July 1951
Profession:	Hydrologist
Position in firm:	Senior Scientific Officer
Specialisation in firm:	Applied Hydrology
Years with firm:	7 - permanent full-time staff member

Key Qualifications

1979 to date — Research hydrologist in Applied Hydrology Division.
* Manages IH reservoir floods research programme.
* Applied research into improved methods of real time flood forecasting.
* Support and development of UK methods of design flood estimation.
* Operational studies of fenland catchments.
* Consultancy studies of UK applied hydrology problems.

1976 - 1979 — Hydrologist with North West Water Authority. Provided a water resource and hydrological analysis and reporting service.

1972 - 1975 — Research student in Engineering Mathematics Department, University of Newcastle-upon-Tyne. Ph.D thesis: Deterministic modelling of catchment systems.

Education

1968 — GCE 'A' levels - Mathematics, Further Mathematics, Physics, Geometrical & Engineering Drawing, General Studies.

1972 — B.Sc (1st Class Hons) in Applied Mathematics and Computing Science, University of Sheffield.

1976 — Ph.D in Applied Science, University of Newcastle-upon-Tyne.

Membership of Professional Institutions

Elected 1978 — AFIMA Associate Fellow of the Institute of Mathematics and its Applications.

Admitted 1979 — MIWES Member of the Institution of Water Engineers and Scientists

Experience

1984 to date	Supervises three commissioned research projects concerned with reservoir flood safety, examining: * spatial aspects of storm hazard on reservoired catchments * improved methods of design flood estimation * extreme rainfall variations in upland areas
1983 to date	Operational studies of land drainage pumping stations and catchments. Development and implementation of pump decision algorithms for real-time control.
1981 to date	Consultancy studies of a wide range of UK applied hydrology problems (see "Consultancy work").
1979 to date	Applied research into improved methods of real time flood forecasting: * preparation of comprehensive review of British flood forecasting practice * case studies of flood forecasting problems in Wales, England and Scotland Support and development of UK methods of flood estimation: * basic research on rainfall/runoff methods * prepares and edits Supplementary Reports in the Flood Studies Report series * teaches FSR methods of flood estimation
1983 - 1986	UK representative to HOMS * coordinated UK contribution to HOMS - a technology transfer subprogramme of the World Meteorological Organization * expert on real time flow forecasting methods
1982 - 1983	Chairman of Computer User Group * represented approx. 70 computer users in negotiations with the computer service organization
1976 - 1979	Hydrologist with North West Water Eastern Division. Provided a water resource and hydrological analysis and reporting service for the division, including: * operating rule studies for Lake District water resource system (Thirlmere, Haweswater, Ullswater and Windermere) * design flood calculations for 13 reservoirs * liaison on technical computer applications
1972 - 1975	Research student, Department of Engineering Mathematics, University of Newcastle-upon-Tyne. Ph.D thesis: Deterministic modelling of catchment systems, 248 pp.

Consultancy Work

1986 to date	Eastbourne Park District Plan (independent review of hydrological assumptions in redevelopment of low lying area). Joint study with Binnie & Partners for Eastbourne Borough Council.
1986 to date	Kennet Valley study (flood risk assessment for development control; flood plain modelling). Joint study with Sir Alexander Gibb & Partners for Thames Water.
1986	Barracks Brook flood study (analysis of detention ponds). Report to Bryant Homes Ltd.
1985 - 1986	Rhyd-y-Car flood study (investigation of catastrophic culvert failure). Contribution to reports by Sir Alexander Gibb & Partners to National Coal Board Legal Department.
1985	Low flow forecasting to aid regulation of the river Wye. Report and software to Welsh Water Authority.
1984 - 1985	Garnant flood study (design flood estimates; land use change effects). Contribution to reports by Sir Alexander Gibb & Partners to National Coal Board Opencast Executive. Preparation of proofs of evidence.
1984	Foudry Brook flood study (design flood estimates for developing catchment). Report to Bryant Homes Ltd.
1984	Digitising circular flow charts. Report and software to Southern Water Authority.
1984	Flood warning system, Dumfries - feasibility study. Report to Solway River Purification Board.
1983	Warminster flood study (design flood estimates for developing catchment, study of chalk catchment data). Report to Lemon & Blizard consulting engineers.
1983	Estimation of return period of December 1979 flood peak on Tawe catchment, South Wales. Report to solicitor.
1982	Water supply reliability studies: the dependence of supply confidence on peak demand and residual resources and the dependence of peak demand on climatic factors. Reports to Southern Water Authority.
1981	Hadlow flood study (design flood estimates for culvert dispute). Report to Southern Water Authority.

Publications

REED, D.W., JOHNSON, P., FIRTH, J.M. (1975), "A non-linear rainfall/runoff model providing for variable lag time". J.Hydrol., 25, 295-305.

LOWING, M.J., REED, D.W. (1980), "Recent advances in flood estimation techniques based on rainfall-runoff". Inst.Civ.Engrs. Conf., Flood Studies Report - five years on. Paper 6. Thomas Telford Ltd, London: 49-56.

BOORMAN, D.B., REED, D.W. (1981), "Derivation of a catchment average unit hydrograph". Institute of Hydrology Report, No.71, 50 pp.

REED, D.W. (1982), "Real time flood forecasting by rainfall/runoff modelling - a case study". Report to Welsh Water Authority, 88 pp.

HOSKING, J.R.M., REED, D.W. (1983), Communication on "Development and operational strategies for water resource and supply systems". J.Inst. Water Engrs. and Scientists, 37, 72-74.

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INSTITUTION OF WATER ENGINEERS AND SCIENTISTS (1987), Co-authored Chapter 4: "Flood warning", in IWES Water Practice Manual No.7: "River Engineering I".

Language Capability

	Speaking	Reading	Writing
English	Excellent	Excellent	Excellent

Signature Date

Curriculum Vitae

Name of firm:	Institute of Hydrology
Name of person:	John Charles PACKMAN
Nationality:	British
Date of birth:	28 October 1951
Profession:	Hydrologist
Position in firm:	Senior Scientific Officer
Specialisation in firm:	Strategic research on urban drainage design and the effects of urbanisation on flood magnitudes
Years with firm:	12 - permanent full-time staff member

Key Qualifications

1979 to date — Leader of Urban Hydrology Research Project.

Developing (i) improved methods of storm sewer design and (ii) methods of estimating the effects of urbanisation on flood magnitudes and frequencies in watercourses downstream.

Writing research reports and contributing to design manuals, in particular:

* Studies in urban hydrology, Institute of Hydrology research report
* The design and analysis of urban storm drainage. The Wallingford Analysis of Storm Sewer Package (WASSP) Manual produced by the DCE/NWC Working Party on the Hydraulic Design of Storm Sewers.
* Guide to the design of storage ponds for flood control in partly urbanised catchment areas. Technical Note produced by the Construction Industry Research and Information Association.

Advising and assisting on a number of small, one off studies of urban drainage problems for the water industry at large.

1975 - 1979 — Member of urban hydrology research team, concerned mainly with the effects of urbanisation on flood response.

1974 - 1975 — Member of applied hydrology research team participating in a number of flood estimation studies for urban and rural catchments, including the River Lagan in N. Ireland.

Education

B.Sc (2:2) in Civil Engineering, Bristol University, 1973.
M.Sc, D.I.C., Engineering Hydrology, Imperial College London, 1974.
Associate Member, Institution of Civil Engineers.

Experience

1975 to date	Senior hydrologist concerned with flood estimation, particularly in urban and urbanising catchments. Main experience is in rainfall-runoff modelling including unit hydrograph/rainfall loss models, linear and non-linear conceptual models, reservoir routing models, and river routing by Muskingum and convective-diffusion techniques. Experience also in statistical hydrology including distribution fitting, regional analysis, and the relationship of rainfall and runoff return periods. Specific studies include the following.
1975 to date	Continued long term investigation of the effects of urbanisation on rainfall-runoff response and statistical flood frequency characteristics of a catchment. Review of worldwide techniques, review of UK data, model development and fitting, regionalisation of parameters. Results published in several reports and papers.
1985 - 1987	Development of semi-distributed model of rainfall-runoff response in mixed urban and rural catchments.
1983 - 1984	Development of programs for data processing and quality control of urban rainfall-runoff data.
1982 - 1983	Development of WASSP model for use in arid climates, in particular - Saudi Arabia and Kuwait.
1977 - 1980	Development of Wallingford Analysis of Storm Sewers Package (WASSP), including computer programming, applications and analysing sensitivity of model to input data.
1980, 1982	Consultant in Brazil on UNESCO project to study the effect of urbanisation in the Diluvio river basin, Porto Alegre. Review of available data, development of model on local computer, analysis of change in runoff volumes and response times.
1979 - 1980	Development of a simple rainfall-runoff model of sewered catchments for inclusion as a planning option in the Wallingford Analysis of Storm Sewers Package. Surface routing and pipflow handled separately using a non-linear reservoir and Muskingum pipe routing.
1978 - 1979	Study of return periods of rainfall and runoff for urban drainage design, including Monte Carlo simulation and distribution fitting. Results incorporated in DOE/NWC design manual.
1978 - 1979	Development of rapid methods for the sizing of flood storage ponds in urban areas. Reservoir routing and attenuation methods. Procedures incorporated in CIRIA design manual.
1975 - 1976	Development of data processing programs for digitisation and quality control of rainfall and runoff charts, with particular reference to urban hydrology.

1974 - 1975 Participation in rainfall-runoff study of the river Lagan, N. Ireland. Data processing, unit hydrograph analysis and regionalisation.

Publications

PACKMAN, J.C. (1976), 'The effect of urbanisation on flood magnitude and frequency'. In: Man's impact on the hydrological cycle in the United Kingdom, ed. G.E. Hollis, Geo Abstracts Ltd, Norwich, UK.

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PACKMAN, J.C. (1979), 'Selection of hydrological input to rainfall-runoff models for use on drainage design'. Guest Author to Yugoslav Conference on Urban Hydrology, Novi Sad.

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PACKMAN, J.C. (1980), 'The effects of urbanisation on flood magnitude and frequency'. IH Report 63.

PACKMAN, J.C., KIDD, C.H.R. (1980), 'A logical approach to the design storm concept'. Water Resources Research, Vol.16, No.6, pp.994-1000.

PACKMAN, J.C. (1980), 'The effect of urbanisation on flood flows'. Institution of Civil Engineers Conference on "Flood Studies Report - 5 years on", Manchester 1980.

PACKMAN, J.C., COLE, G.A., ROBINSON, M. (1981), 'Stormwater simulation using the Wallingford sewered subcatchment model'. 2nd International Conference on Urban Storm Drainage, Urbana, Illinois, USA.

BARNSLEY, R., PRICE, R.K., PACKMAN, J.C. (1984), 'Application of the Wallingford procedure to the design of urban stormwater drainage for Jeddah, Saudi Arabia.' Planning, Construction, Maintenance and Operation of Sewerage Systems, Reading.

PACKMAN, J.C. (in press), 'Runoff estimation in urbanising and mixed urban/rural catchments'. Sewers for Adoption, April 1986.

ACREMAN, M.C., PACKMAN, J.C. (in press), 'Semi-distributed rainfall-runoff modelling on the River Almond'. Hydrology in Scotland.

Language Capability

	Speaking	Reading	Writing
English	Excellent	Excellent	Excellent
French	Fair-Poor	Fair	Fair-Poor
Portuguese	Some	Some	-

Signature

Date

ANNEX IV

PUBLISHED PAPERS RELEVANT TO PROJECT

Invited paper, Symposium on Flood Warning Systems, Winter Meeting of the River Engineering Section, The Institution of Water Engineers and Scientists, 24 January 1986.

ADVANCES IN REAL-TIME FLOOD FORECASTING PRACTICE

R.J. Moore

Institute of Hydrology

ABSTRACT

Advances in flood forecasting practice have been traditionally achieved through developing improved model structures representing rainfall-runoff and channel flow routing processes. Only over the last decade has the availability of low cost real-time data acquisition systems promoted new research on the development of updating techniques which employ current measurements of flow to improve model-derived flow forecasts. Several different updating techniques have been developed for use in practical flood forecasting systems: the relative merits of a selection of these are discussed. Particular emphasis is given to adjustment of the water content of a conceptual model storage to compensate for the cumulative effect of unrepresentative or error-corrupted rainfall data.

Developments of improved model structures are reviewed with particular regard to recent attempts to take account of spatial variability through a probability-distributed model structure, and through the use of distributed rainfall data, as measured by weather radar. Problems of model calibration, forecast uncertainty, and provision of rainfall forecasts are also touched upon as requiring attention in the future.

INTRODUCTION

Flow forecasts are required to provide warning of impending flooding in order to prevent loss of life and to minimise damage to property, livestock etc. Advances in real-time data acquisition systems over the last ten years, and a reduction in their cost in real terms, has promoted the implementation of real-time systems for flood forecasting in several areas of the UK (Reed, 1984). Implementation of such systems has required research on the development of flood forecasting techniques which can be implemented in real-time on a micro-computer, and which attempt to make use of current information on the river basin's state as provided through telemetered measurements of rainfall and river flow. The aim of this paper is to review some of the techniques which have been developed as part of this research effort, and to discuss their relative shortcomings and advantages. Some areas where further research is required are also identified.

FLOOD FORECASTING TECHNIQUES

Flood forecasting practice may be advanced through research on

(i) improved model structures,

(ii) improved updating techniques,

(iii) improved specification of input data, and

(iv) improved specification of measures of forecast uncertainty.

Improvement in model structure has been the traditional approach to enhance forecast performance, and indeed the design of rainfall-runoff and channel flow routing models suitable for real-time implementation remains of central importance. However, the real-time aspect of flood forecasting, with the ability to correct previous forecasts in the light of up-to-date flow data, received via telemetry, has meant that the development of updating techniques has formed the major thrust of research over the last decade. For this reason a selective review of updating techniques will be presented first, giving emphasis to those techniques which have merit for practical flood forecasting application, rather than on account of their intrinsic statistical elegance.

UPDATING TECHNIQUES

Updating of model forecasts may be accomplished by

(i) error prediction, where the tendency for errors to persist is exploited in order to predict future errors,

(ii) parameter adjustment, and

(iii) state adjustment, where corrections are made to the water content of internal storages to achieve closer correspondence between measured and predicted flow.

Techniques used for parameter and state adjustment are often based on some form of Kalman filter (Gelb, 1974; Jazwinski, 1970; Moore and Weiss, 1980). Parameter adjustment presents a less attractive option for real-time application since variation in a model parameter usually reflects inadequacy in the model structure, which should preferably be improved by off-line studies. Adjustment of parameters to compensate for model inadequacies merely serves to track the variations rather than to anticipate them, and may lessen the robustness of the resulting forecast. Attention here will therefore concentrate on state adjustment.

State adjustment

One justification for making state adjustments is that the effect of errors in the rainfall model input will accumulate as errors in the water content of the stores of a conceptual rainfall-runoff model, which in turn will affect the partitioning of rainfall into surface and groundwater runoff components. If the contents of the stores can be adjusted sensibly in the light of discordance between modelled and observed runoff, then improved forecasts should result. Conventionally, state updating has been achieved through the Kalman filter. However, whereas this theory provides an exact solution for linear models even when the random variations may be non-Gaussian, it only provides approximate solutions for nonlinear conceptual rainfall-runoff models. There is therefore considerable scope for developing empirically-based state adjustment procedures which sensibly exploit the hydrologist's insight into the physical mechanisms, and are not restricted in applicability to specific simplified dynamic-stochastic descriptions of the rainfall-runoff process.

One simple example of a state updating scheme may be illustrated with reference to a nonlinear storage model, where runoff, q, is related to basin water storage, S, through a relationship $q = k\,S^m$ or $q = \exp(\gamma + aS)$. In such cases flow at time t, q_t, is related to flow at time t-1, by a nonlinear function f(.), such that $q_{t+1} = f(q_t, u_{t-b}; k, m)$, where u_{t-b} is rainfall delayed by b time units. A simple state updated forecast is then obtained by evaluating the function f(.) using the observed value of discharge, Q_t, so that $q_{t+1|t} = f(Q_t, u_{t-b}; k, m)$. Here the notation $t+1|t$ forecast made for time t+1 based on measurements available at time t, the forecast time origin. Note that this adjustment implies that the storage (the state variable) is adjusted to the value $(Q_t/k)^{1/m}$ in order to satisfy the relation $q = kS^m$.

Adjustment schemes are not so readily devised for conceptual rainfall-runoff models made up of several storages, however. Recourse may be made to adjustments having a form similar to those arising from the Kalman filter. For example, consider a model comprised of two storages with contents S_t^1 and S_t^2 at time t, and with outputs q_t^1 and q_t^2 so that the total model flow is $q_t = q_t^1 + q_t^2$. Then the model error, $\eta_t = Q_t - q_t$, may be partitioned between the two storages to give the state adjustment scheme

$$S_t^{i*} = S_t^i + K^i\,(Q_t - q_t) \qquad i=1,2, \qquad (1)$$

where K^i is a parameter, essentially equivalent to the Kalman gain, which would be estimated empirically by an off-line optimisation based on observed flow data. One possible extension is to allow the two gain parameters to vary according to the relative contribution of surface runoff, q_t^1, and baseflow, q_t^2, to the total flow q_t; for example K^i in (1) could be replaced by K_t^i, given by

$$K_t^i = \left(\frac{q_t^i}{q_t} \right) K^i \qquad i=1,2. \tag{2}$$

Clearly a wide range of state adjustment procedures may be devised, including subjective schemes based on visual interpretation of the discrepancy between components of model flow and the total observed runoff. State adjustment may also be used to good effect to initialise a model using a minimum of past data, possibly in the event of a breakdown of the data acquisition system.

Error prediction

The most commonly used form of updating technique, and one which can now be regarded as part of established forecasting practice, is error prediction (Moore, 1982; Jones and Moore, 1980). Both rainfall-runoff and channel flow routing models exhibit a tendency for their errors to persist so that sequences of positive errors (underestimation) or negative errors (overestimation) are common. This dependence structure in the errors may be exploited by developing error predictors which incorporate this structure and allow future errors to be predicted. The essentials of the technique may be described as follows.

Consider that $q_{t+\ell}$ is the forecast of the observed flow, $Q_{t+\ell}$, at some time $t+\ell$, made using a conceptual rainfall-runoff model. Since $q_{t+\ell}$ will have essentially been obtained by transformation of rainfall into flow through some model conceptualisation of the catchment, it will not have used previous observed values of flow, except perhaps for the purposes of model initialisation. For this reason $q_{t+\ell}$ will be referred to as a simulation-mode forecast to distinguish it from a real-time, updated forecast which incorporates information from observed flows.

The error, $\eta_{t+\ell}$, associated with this simulation-mode forecast is defined through the relation

$$Q_{t+\ell} = q_{t+\ell} + \eta_{t+\ell} \quad . \tag{3}$$

If the simulation-mode error $\eta_{t+\ell}$ can be predicted using an error predictor which exploits the dependence structure of these errors, then an improved forecast will be obtained.

Let $\eta_{t+\ell|t}$ denote a prediction of the simulation-mode error, $\eta_{t+\ell}$, made ℓ steps ahead from a forecast origin at time t using an error predictor. Then a real-time forecast, $q_{t+\ell|t}$, made ℓ time units ahead from a forecast origin at time t would be calculated as follows:

$$q_{t+\ell|t} = q_{t+\ell} + \eta_{t+\ell|t} \quad . \tag{4}$$

The real-time forecast error is

$$\varepsilon_{t+\ell|t} = Q_{t+\ell} - q_{t+\ell|t} \tag{5}$$

which, depending on the performance of the error predictor, should be smaller than the simulation-mode forecast error

$$\eta_{t+\ell} = Q_{t+\ell} - q_{t+\ell} \quad . \tag{6}$$

Turning now to an appropriate form of error predictor it is clear that a structure which incorporates dependence on past simulation-mode errors is required. Thus the autoregressive (AR) model

$$\eta_t = - \phi_1 \eta_{t-1} - \phi_2 \eta_{t-2} - \dots - \phi_z \eta_{t-z} + a_t \tag{7}$$

is an obvious candidate, where a_t is the residual error (uncorrelated), and $\{\phi_i\}$ are parameters. However, a more parsimonious form of model is of the autoregressive-moving average (ARMA) form

$$\eta_t = - \phi_1 \eta_{t-1} - \phi_2 \eta_{t-2} - \dots - \phi_p \eta_{t-p} + \theta_1 a_{t-1} + \theta_2 a_{t-2}$$

$$+ \dots + \theta_q a_{t-q} + a_t \tag{8}$$

which incorporates dependence on past residual errors, a_{t-1}, a_{t-2}, ... In general, the number of parameters p+q associated with the ARMA model will be less than the number z associated with the AR model, in order to achieve as good a level of approximation to the true simulation-mode error structure. The ARMA model may be used to give the following error predictor

$$\eta_{t+\ell|t} = - \phi_1 \eta_{t+\ell-1|t} - \phi_2 \eta_{t+\ell-2|t} - \dots - \phi_p \eta_{t+\ell-p|t} + \theta_1 a_{t+\ell-1|t}$$

$$+ \theta_2 a_{t+\ell-2|t} + \dots + \theta_q a_{t+\ell-q|t}, \; \ell=1,2,\dots \tag{9}$$

where

$$a_{t+\ell-i|t} = \begin{cases} 0 & \ell-i>0 \\ a_{t+\ell-i} & \text{otherwise} \end{cases} \tag{10}$$

and $a_{t+\ell-i}$ is the one-step ahead prediction error

$$a_{t+\ell-i} \equiv a_{t+\ell-i|t+\ell-i-1} = \eta_{t+\ell-i} - \eta_{t+\ell-i|t+\ell-i-1}$$

$$= Q_{t+\ell-i} - q_{t+\ell-i|t+\ell-i-1}, \quad (11)$$

and

$$\eta_{t+\ell-i|t} = \eta_{t+\ell-i} = Q_{t+\ell-i} - q_{t+\ell-i} \qquad \text{for } \ell-i<0. \quad (12)$$

The prediction equation (9) is used recursively to produce the error predi- tions $\eta_{t+1|t}$, $\eta_{t+2|t}$, ..., $\eta_{t+\ell|t}$, from the available values of a_t, a_{t-1}, ... and η_t, η_{t-1}, ...

Using this error predictor methodology, the conceptual model simulation-mode forecasts, $q_{t+\ell}$, may be updated using the error prediction, $\eta_{t+\ell|t}$, obtained from (9) (and the related equations (10)-(12)), to calculate the required real-time forecast, $q_{t+\ell|t}$, according to equation (4). Note that this real-time forecast incorporates information from most recent observations of flow through the error predictor, and specifically through calculation of the one-step ahead forecast errors, $a_{t+\ell-i}$, according to equation (11). Alternative error predictor schemes may be devised by working with other definitions of the basic errors : for example by using proportional errors.

Whilst error prediction provides a general technique which is easy to apply, its performance in providing improved forecasts will depend on the degree of persistence in the model errors. Unfortunately in the vicinity of the rising limb and peak of the flood hydrograph this persistence is least and errors show a tendency to oscillate rapidly and most widely; dependence is at its strongest for errors on the falling limb, where improved forecast performance matters least. In addition, timing errors in the model forecast may lead to erroneous error prediction corrections being made (Figure 1), a problem which is also shared by the technique of state adjustment. For these reasons it is important that the deterministic model structure is well specified first and foremost.

MODEL STRUCTURES

Black box modelling and the systems approach to hydrological forecasting became fashionable in the 1970's, motivated in particular by

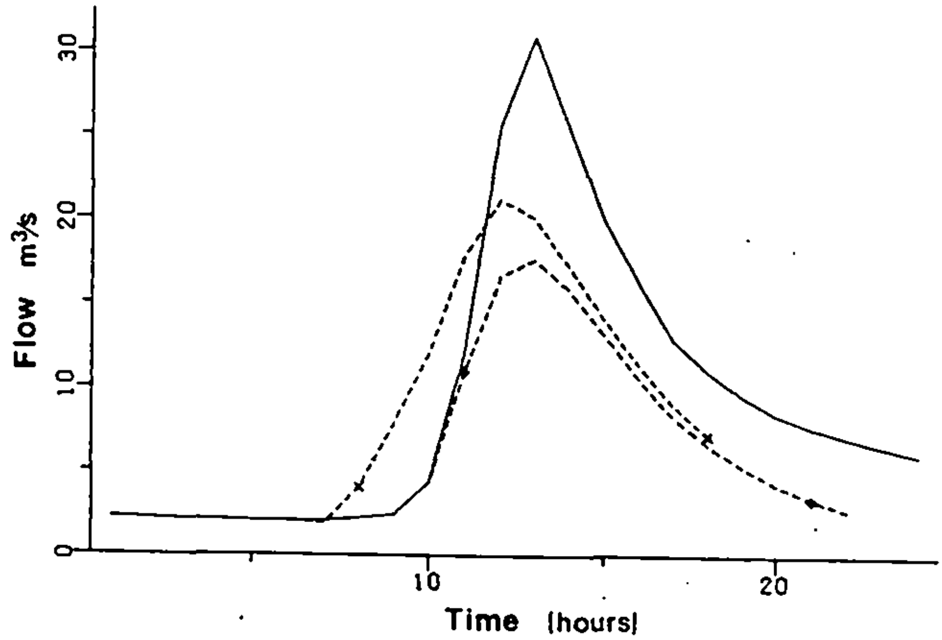

Figure 1 Flow forecasts made up to 12 hours (12-steps) ahead for the Eden at Kirkby Stephen from two origins to show the effect of model timing error on forecasts updated using an error predictor (perfect knowledge of future rainfall is assumed for lead times beyond one hour)

the text by Box and Jenkins (1970) entitled Time Series Analysis, Forecasting and Control. Conceptual models grew out of favour, research hydrologists recognising that the more conceptually developed they became the more parameters they required and the greater were the difficulties of calibrating the model parameters. The number of conceptual models available proliferated, most being variations on similar themes. However in the 1980's hydrologists are now recognising the shortcomings of black box models to adequately represent the nonlinear response of hydrological systems, and conceptual models are now reasserting themselves as useful forecasting tools in certain instances. Indeed the two approaches may be used in a complementary manner. The transfer function of black-box modelling may be used to represent a storage routing element in a conceptual model and an ARMA model may be used as the basis of the error prediction methodology previously discussed for enhancing conceptual model forecasts. Indeed, the equivalence of specific transfer functions to a number of well known routing functions, including that of the Muskingum method, has been established (O'Connor, 1982). Hydrologists have also recognised the equivalence of the transfer function model to the unit hydrograph of classical hydrology (Moore, 1982). This equivalence will be used here to introduce the transfer function model, and the relatively new idea of a continuity constrained transfer function model.

Transfer function models

The transfer function model expresses an output, such as model flow q_t, in terms of a weighted combination of past outputs q_{t-1}, q_{t-2}, ... , and past inputs (eg rainfall or upstream flow), u_{t-b}, u_{t-b-1}, ... where b is a time delay. An example is the transfer function model

$$q_{t+1} = -\delta_1 q_t + \omega_0 u_t + \omega_1 u_{t-1} + \omega_2 u_{t-2} \qquad (13)$$

where δ_1 and $\{\omega_i\}$ are parameters and the time delay b equals unity. Dependence on past flow means that the transfer function model may be readily state updated by substituting the model flow, q_t, with the observed flow, Q_t, on the right hand side of this equation to give the updated forecast

$$q_{t+1|t} = -\delta_1 Q_t + \omega_0 u_t + \omega_1 u_{t-1} + \omega_2 u_{t-2} .$$

Alternatively, error prediction may be accomplished in the normal way via

$$q_{t+1|t} = q_{t+1} + n_{t+1|t}.$$

If u_o represents rainfall in the interval (0,1) and is taken to be unity, and subsequently no rainfall occurs, then for an initially zero flow we have

$$q_o \equiv v_o = 0$$

$$q_1 \equiv v_1 = \omega_o$$

$$q_2 \equiv v_2 = \omega_1 - \delta_1 v_1$$

$$q_3 \equiv v_3 = \omega_2 - \delta_1 v_2$$

$$q_4 \equiv v_4 = - \delta_1 v_3$$

$$q_5 \equiv v_5 = - \delta_1 v_4 \qquad (14)$$

etc.

Consequently we see that the transfer function model may be expressed as

$$q_t = v_o u_t + v_1 u_{t-1} + v_2 u_{t-2} + \ldots \qquad (15)$$

where flow is expressed as a weighted combination of past inputs only; this is illustrated in Figure 2. The weights $\{v_i\}$ are the impulse response function weights and if $\sum_{i=0}^{\infty} v_i = 1$ then (15) represents a unit hydrograph with ordinates $\{v_i\}$, where the inputs $\{u_t\}$ are effective rainfall and $\{q_t\}$ are baseflow separated flows. If the transfer function is subject to a steady unit input so $u_t = u_{t+1} = \ldots = 1$, then q_t g, as t ∞, where g is the steady state gain, and from (13)

$$q_\infty = - \delta_1 q_\infty + \omega_o + \omega_1 + \omega_2$$

giving

$$g \equiv q_\infty = \frac{\omega_o + \omega_1 + \omega_2}{1 + \delta_1} . \qquad (16)$$

An alternative expression arises from the impulse response function equation (15):

$$g = q_\infty = \sum_{i=o}^{\infty} v_i . \qquad (17)$$

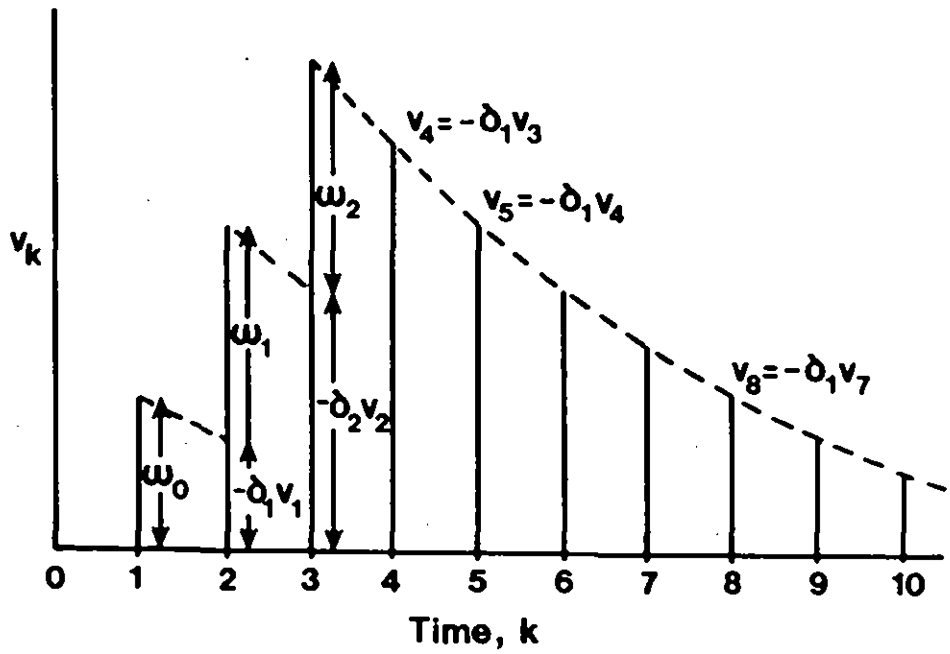

Figure 2 Impulse response function of the transfer function model, $q_t = -\delta_1 q_{t-1} + \omega_o u_{t-1} + \omega_1 u_{t-2} + \omega_2 u_{t-3}$, to demonstrate the relationship between the ordinates, v_k, of the unit hydrograph model and the transfer function model parameters, δ_i and ω_i

For continuity to be preserved we require $g = 1$, which also ensures exact equivalance between the unit hydrograph and transfer function model equations for an effective rainfall input. Imposing continuity on the transfer function model means that

$$\omega_0 = 1 + \delta_1 - \omega_1 - \omega_2 \; . \qquad (18)$$

Consequently a continuity constrained transfer function model may be obtained by estimating δ_1, ω_1, and ω_2 and using the above relation to obtain ω_0. The continuity constrained transfer function is particularly useful for channel flow routing where upstream flow may be transformed to downstream flow using the transfer function, whilst ensuring that volumes are preserved. Lateral inflow would be incorporated using a further transfer function between rainfall over the lateral inflow area and the component of the downstream flow not attributed to the upstream flow: in this case the gain would not be constrained to unity but would be allowed to vary as a function of soil moisture conditions.

The gain of a transfer function model when applied to total rainfall and total runoff is equivalent to the runoff coefficient which is known to vary as a function of soil moisture. The problem of defining the effective rainfall, or the nature of the variation in the gain, as a function of soil moisture (and rainfall intensity), is essentially equivalent to choosing an appropriate loss model in unit hydrograph theory. As a consequence the importance of loss accounting to storm runoff production is shared by transfer function and unit hydrograph approaches. Most loss accounting methods are rather ad hoc and inadequate. Primarily on account of these shortcomings, attention has turned back to conceptual models which maintain a water balance over time of soil moisture and groundwater storage. Particularly inappropriate for flood forecasting is the use of loss models which require soil moisture deficit estimates as part of a unit hydrograph procedure. These deficit estimates require continuous soil moisture accounting using rainfall and evaporation data but largely ignore runoff production. More satisfactory for forecasting purposes is the integrated approach to soil moisture, groundwater and runoff production that the conceptual rainfall-runoff provides.

Conceptual models

Conceptual models may simply characterise runoff production using a single soil moisture storage, represented mathematically by the nonlinear storage model

$$\frac{dq}{dt} = a\,(u - q)q^{b}\ , \qquad (19)$$

which derives from the storage equations $q = k\ S^{m}$ when $b \neq 1$, and $q = \exp(\gamma + aS)$ when $b = 1$ (Moore, 1983). Here, the parameter $a = m\ k^{1/m}$ and $b = (m-1)/m$. The input, u, may be total rainfall, effective rainfall obtained from a loss accounting procedure, or flow at an upstream location. However, more generally conceptual models are made up of a number of model elements representing different water storages and translation processes operating within a river basin. Recent research has accepted the conceptual model's inherent advantage over transfer function models in better representing nonlinear hydrological systems, and has turned to improve upon some of their shortcomings. A principal problem is the difficulty of model calibration because ofthe large number of parameters that are often involved. Further problems arise from the threshold type response functions which are often employed: these lead to discontinuities in the derivatives of the objective function surface being searched. Such problems have been reviewed by Johnston and Pilgrim (1976), Moore and Clarke (1981), and Gupta and Sarooshian (1985).

Another area of research has been to consider how the lumped nature of conceptual models may be relaxed in order to incorporate spatial variation in runoff production over a basin. Moore and Clarke (1981) showed how spatial variability in point storage capacity over a basin could be represented probabilistically within a rainfall-runoff model, and in so doing transform a threshold model function, and an associated non-differentiable model objective function surface, into a probability-distributed model function having a continuously differentiable model objective function surface. The essential aspects of this probability-distributed approach to modelling runoff production are as follows. Assume that runoff production at a point is controlled by a threshold excess mechanism, such that rainfall exceeding a given threshold will generate runoff. This threshold may correspond to the soil's capacity to store water (the storage capacity), or to the maximum rate that water can enter the soil surface (the infiltration capacity). The threshold excess mechanism may be represented by

$$q = \begin{cases} p-c & p > c \\ 0 & p < c \end{cases} \qquad (20)$$

where c is the threshold capacity, p the rainfall, and q the runoff. Spatial variation of threshold capacity over a basin may be described by a probability density function, f(c), such that f(c)dc denotes the probability of threshold capacity at any point in the basin being in the range (c, c+dc). The function F(c) will be used to denote the corresponding cumulative distribution function.

If rainfall falls at a rate p then according to the infiltration excess mechanism, only points with capacities less than p will generate direct runoff, so the instantaneous rate of runoff production per unit area is

$$q = \int_o^p (p-c)\ f(c)dc = \int_o^p F(c)dc\ . \qquad (21)$$

Assuming for purposes of illustration that the threshold capacity is exponentially distributed over the basin, so that $f(c) = \bar{c}^{-1} \exp(-c/\bar{c})$, where $\bar{c}$ is the mean threshold capacity, then

$$q = p - \bar{c}\ (1 - \exp(-p/\bar{c})). \qquad (22)$$

In contrast, for the storage capacity excess mechanism the entire basin will absorb all rainfall initially until the soil moisture deficits are replenished at some points. Consequently, assuming an initially dry basin, the rate of runoff production initially will be zero. At the end of a unit interval during which rainfall occurs at a uniform rate p, all points in the basin with storage capacities less than p will be saturated and will generate runoff at a rate p, whilst the remainder of the basin will absorb all rainfall. Thus the proportion of the basin generating runoff will be

$$\text{prob}(c < p) = F(p) = \int_o^p f(c)dc, \qquad (23)$$

and the area contributing to runoff will be

$$A_c = F(p)A\ , \qquad (24)$$

where A is the area of the basin. The instantaneous rate of runoff production per unit area from the entire basin will be

$$q = F(p)\, p \,. \tag{25}$$

Specifically for an assumed exponential distribution of storage capacity over the basin

$$q = p(1 - \exp(-\, p/\bar{c}))\,, \tag{26}$$

where $\bar{c}$ denotes the mean storage capacity. Extensions of these basic ideas to include evaporation and drainage to groundwater as part of a continuous basin water balance calculation are presented in Moore (1985a). Application of the probability-distributed principle to runoff production by a threshold excess mechanism essentially provides a novel loss accounting model determining the volume of storm runoff for given rainfall and soil moisture conditions. It also provides a model function which, being continuously differentiable, is particularly suitable for use with automatic parameter estimation techniques (Moore and Clarke, 1981). The runoff produced must then be routed to the basin outlet in the normal way using storage routing or convolution methods to obtain a model prediction of the observed basin runoff. Figure 3 shows how the probability-distributed model of storage capacity may be used as one model element of a conceptual rainfall-runoff model. An example of forecasts of flow and soil moisture deficit obtained using this model are displayed in Figure 4. Table 1 provides a summary of error statistics obtained when the model is augmented by an error predictor.

The probability-distributed principle may also be invoked to take account of spatial variability in rainfall over a river basin. The distribution of rainfall over a basin may be represented by a probability density function, fp(p), such that fp(p)dp denotes the probability of rainfall at any point within the basin being in the range (p, p+dp). Runoff production per unit area from the entire basin will then be given by

$$q = \int_0^\infty \int_c^\infty (p-c)\, f_p(p)\, f(c)\, dp\, dc \tag{27}$$

where, as before, f(c) is the probability density function of threshold

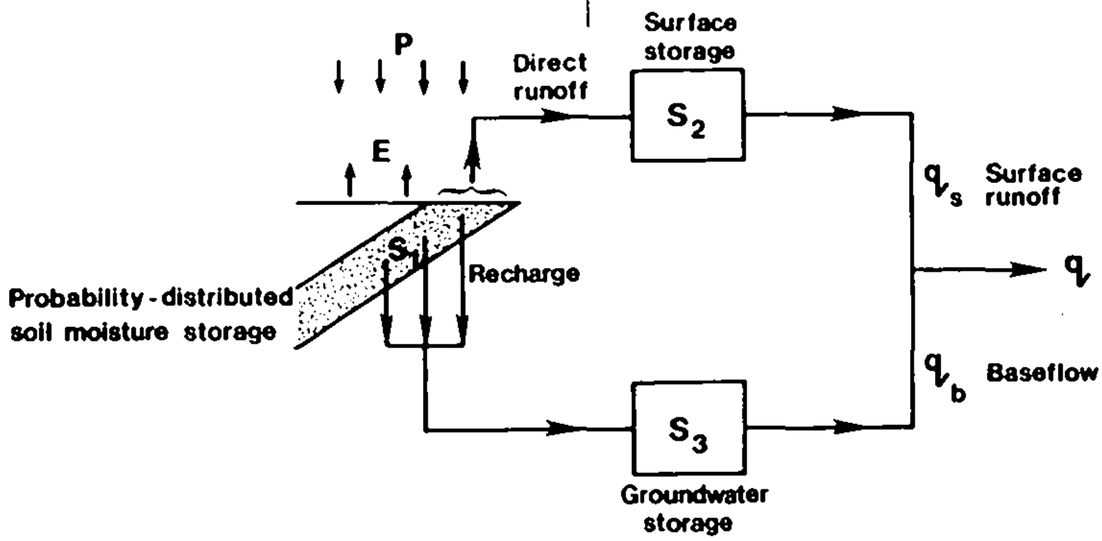

Figure 3 Conceptual rainfall-runoff model comprised of a probability-distributed soil moisture storage to effect the separation of runoff into surface and baseflow components, and two storage routing components to effect the translation of surface and groundwater runoff to the basin outlet

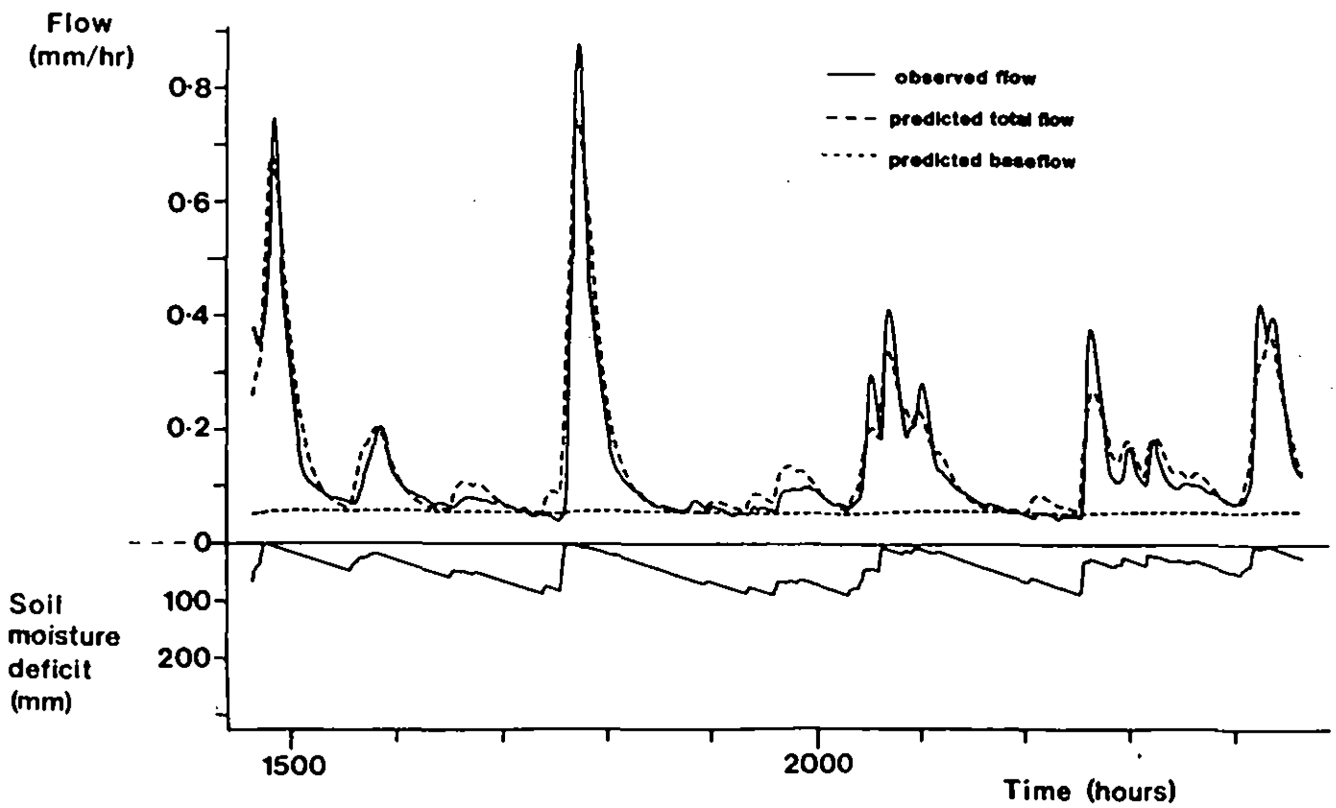

Figure 4 Simulation-mode forecasts of flow and soil moisture deficit for the probability-distributed conceptual model of Figure 3; hourly flow data for the Mole at Kinnersley Manor, 1 January to 11 February 1977

Table 1. Error statistics for the probability-distributed conceptual model of Figure 3, when updated using the error predictor, $\eta_{t+\ell|t} = 1.553\ \eta_{t+\ell-1|t} - .616\ \eta_{t+\ell-2|t} + .427\ a_{t+\ell|t}$; hourly flow data for the Mole at Kinnersley Manor, 1 January to 31 March 1977

lead time (hours)	Root mean square error	R^2	Mean absolute % error in peak forecasts	% error for largest peak
1	.0048	.998	1.4	2
3	.0152	.978	4.0	1
6	.0264	.933	18.7	23
Simulation-mode	.0318	.905	18.5	16

infiltration capacity. Assuming that both densities are exponential this yields the following simple nonlinear relation between rainfall and runoff (Moore, 1985b)

$$q = \frac{\bar{p}^2}{\bar{p} + \bar{c}}, \qquad (28)$$

where $\bar{p}$ and $\bar{c}$ are the mean rainfall and threshold capacity respectively (Figure 5). This extension to accommodate spatially distributed rainfall is as yet not fully developed, and its utility for flood forecasting requires evaluation. However, it does appear to provide a novel way of making better use of distributed rainfall data obtained from weather radar. Grid square values of rainfall over a basin could be used to identify the form and parameters of the density fp(p) for successive time frames as the storm develops.

AREAS FOR FUTURE RESEARCH

This selective review has presented a consolidation of findings gained from recent research, giving emphasis to techniques which have proved useful in practice, and others which show promise, but have still to be evaluated fully. A retrospective look at research on real-time flood forecasting since 1970 shows that, for a time, research displayed a preoccupation with theoretical aspects of state-parameter estimation, and an emphasis on statistical model structures, at the expense of those of a more realistic, hydrological kind. In the 1980's, interest in problems of parameter estimation have shifted from an emphasis on recursive estimation schemes of the Kalman filter type, to problems associated with more traditional off-line objective function minimisation when applied to conceptual rainfall-runoff models. This most recent research is concerned with analysing the errors of a conceptual rainfall-runoff model in a statistical framework (eg. Troutman, 1985). A detailed statistical analysis of the errors not only has the potential to give more reliable parameter estimates, but also

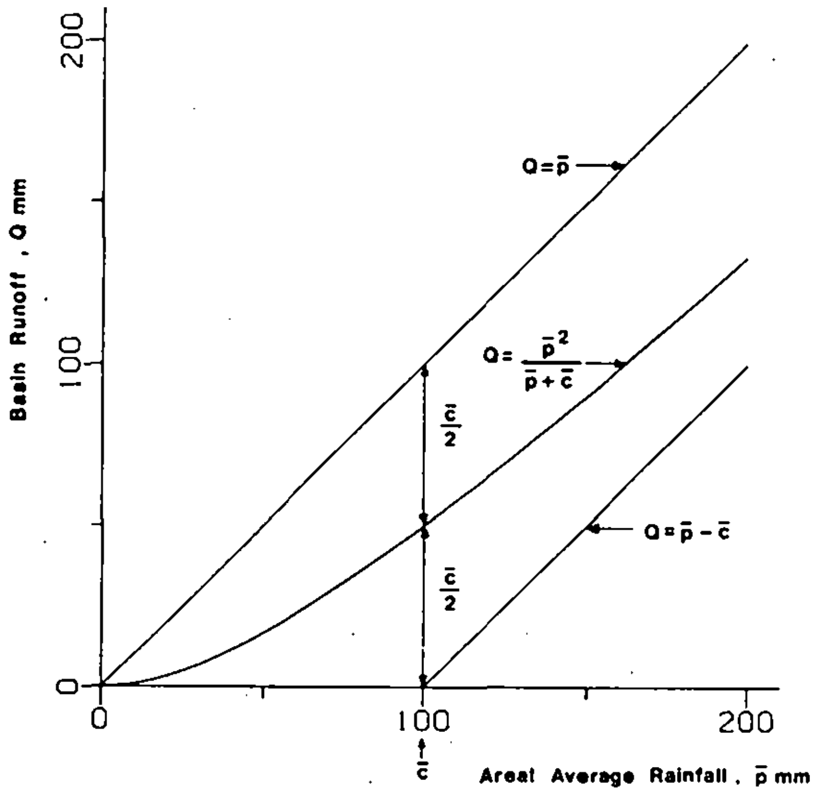

Figure 5 Rainfall-runoff relationship implied by the probability-distributed model of rainfall and runoff production

allows uncertainty of these estimates to be specified, and more importantly, also allows the uncertainty of the forecast itself to be specified. The ability to properly quantify the uncertainty associated with a forecast is clearly of great importance since it allows the decision-maker to better ascertain the risk of issuing a false warning or of not providing a warning at all in the event that a flood does actually occur. Whilst techniques based on Kalman filters and transfer function noise models apparently provide a measure of forecast uncertainty, the dynamic-stochastic system assumed is often not a good reflection of the hydrologic system, neither in its dynamic nor in its stochastic part. As a consequence, the forecast uncertainty it provides is incorrect and is often poor in practice, especially in the vicinity of the rising limb and peak of the hydrograph. Cooper (1983) has begun to address the problem of assessing the uncertainty associated with flood forecasts by considering floods as quasi-replicates. A simple, and practical approach to derive estimates of forecast uncertainty, though as yet undeveloped, is through an empirical analysis of the errors resulting from the application of the forecasting technique to historical data (Jones and Moore, 1985). The root mean square of these errors could be calculated over a range of different forecasted flood magnitudes, for example, and these used as the basis of uncertainty bounds in real-time. Other extensions are possible, such as exploring how the size of root mean square error varies as a function of both flood magnitude and hydrograph rate of rise.

No matter what improvements are made to the structure of rainfall-runoff models and to techniques for forecast updating, their accuracy at higher lead times will continue to depend very much on the availability of good rainfall forecasts. Current practice is to utilise either meteorological synoptic forecasts, or to construct simple statistical models based on an autoregressive-moving average structure. Research results on the use of weather radar and Meteosat cloud imagery to replace existing synoptic forecasts over the short-term appears promising (Browning and Carpenter, 1984). Particularly valuable is radar's ability to portray the pattern of rainfall over space and to allow the movement and development of the pattern to be monitored over time. Radar is now seen as a useful qualitative visual tool by a majority of flood warning authorities in England (Reed, 1984). However it will probably not be before the end of the current decade that we will be in a position to establish the true value of weather radar as a quantitative tool for flood forecasting.

CONCLUDING REMARKS

This selective review has presented and discussed a number of techniques which either have proved useful, or appear potentially useful, to improving flood forecasting practice. The techniques are presented as "tools of the trade" rather than as "standards of practice" in the belief that the design of flood forecasting systems should involve exploratory data analysis leading to custom-made solutions. These solutions, as a matter of principle, should be as simple as possible, whilst providing an acceptable answer to the specific forecasting problem of concern. A relatively complex conceptual model may be demanded on account of hydrological complexity, or to satisfy a need to represent flows over the whole spectrum of flows and at a range of lead times. In other situations simple transfer functions or nonlinear storage models may suffice (Lambert, 1972; Brunsdon and Sargent, 1982). Flood forecasts at several points within a river basin are often required and then a semi-distributed model with flow linkages between forecast sites may also be required (Central Water Planning Unit, 1977; Bailey and Dobson, 1981). Model structures and updating techniques presented here present options which should prove helpful in the broader task of developing useful flood forecasting systems.

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TOWARDS MORE EFFECTIVE USE OF RADAR DATA FOR FLOOD FORECASTING

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SUMMARY

The question of how radar data may be more effectively used for flood forecasting is addressed through first understanding the shortcomings of rainfall-runoff models, and how these shortcomings relate to the form of rainfall input they employ. Errors attributed to the rainfall input are not only due to inaccurate estimation of basin average rainfall, but also to a failure to properly account for rainfall's inherent spatial variability.

It is argued that more effective use of radar data for flood forecasting must largely depend on the development of distributed models, capable of real-time implementation. An outline of a simple geometrically-distributed model is presented, together with a novel rainfall-runoff model, which treats rainfall as a probability-distributed variable over the basin. Both models are designed to make better use of weather radar data. Updating techniques capable of employing flow information up to the present to compensate for the effect of past rainfall errors on rainfall-runoff model performance are considered: a scheme based on empirical adjustment of the water content of a conceptual model's store is presented as an attractive alternative to more formal schemes based on the Kalman filter.

The importance of *rainfall forecasts* in order to use a *rainfall-runoff* model to provide adequate warning of impending flooding is emphasised. It is in the area of rainfall forecasting that the flood forecaster's needs, and expectations of radar's usefulness, are greatest. Finally, a more rigorous evaluation, than heretofore, of the benefits of weather radar data to flood forecasting, carried out across a range of hydrological environments, is seen as a crucial requirement for the future.

Paper presented to the Conference of River Engineers 1986, Cranfield 15-17 July (this is a revised version of a paper originally presented to the Symposium on Weather Radar and Flood Forecasting, University of Lancaster, 16-18 September 1986).

INTRODUCTION

In order to speculate on how weather radar may be put to more effective use for flood forecasting in the future, and on the degree of benefit likely to accrue, it is important to understand the major shortcomings of existing flood forecasting procedures. Comparison of flood forecasting models with different structural forms often leads to a result which is not clearcut, with no one model consistently outperforming all others. A threshold of model performance appears to be reached by a range of rainfall-runoff models. The main key to surpassing this threshold of model performance is seen to be an improved estimation of areal rainfall; thus on a priori grounds the likely benefits of weather radar appear very promising indeed.

Scope for improvement using weather radar data appears to exist not only through better definition of the catchment average rainfall used as a lumped input to many rainfall-runoff models, but also in the better use of the spatially distributed rainfall measurements that weather radar provides.However, the use of spatially distributed measurements for flood forecasting first requires the development of rainfall-runoff models which are structured to make greater use of the information on spatial variation in rainfall contained in these data. The development of such models forms a central theme of this chapter. An outline of a simple geometrically-distributed model is presented, together with a novel rainfall-runoff model, which treats rainfall as a probability-distributed variable over the basin. Both models are designed to make better use of weather radar data. Updating techniques capable of employing flow information up to the present to compensate for the effect of past rainfall errors on rainfall-runoff model performance are considered: a scheme based on empirical adjustment of the water content of a conceptual model's stores is presented as an attractive alternative to more formal schemes based on the Kalman filter.

In the concluding sections the case is argued for a more rigorous evaluation than heretofore of the benefits of weather radar data to flood forecasting, carried out across a range of hydrological environments: such an evaluation is seen as a crucial requirement for the future.

INFLUENCE OF RAINFALL ERRORS ON RAINFALL-RUNOFF MODEL FORECASTS

Consideration needs to be given first to the effect on rainfall-runoff model performance of error-corrupted rainfall measurements, either in the form of at-a-point measurement errors or through the failure of a model to take account of the distributed nature of rainfall. This serves to clarify both the potential value of radar-derived measurements of rainfall to flood forecasting, and the implications of their error-corrupted nature to rainfall-runoff model design. It is important to understand the influence of these errors on rainfall-runoff model performance if an appreciation of the potential value of distributed radar rainfall data is to be gained. The following examines the relation of model structure to rainfall input errors, and the error introduced by using a lumped, areal average, rainfall input.

Effect of the structural form of the model

The effect of errors on rainfall measurements used as input to a rainfall-runoff model will depend on the model's structural form. Singh and Woolhiser (1976) demonstrate how a nonlinear rainfall-runoff model tends to amplify the errors so that a linear model calibrated on data simulated from a nonlinear model and using exact rainfall may perform better than the true nonlinear model when the rainfall input is error-corrupted. Singh (1977) demonstrates that even if rainfall is exactly known, the errors introduced in conversion to rainfall excess may mean that a linear routing model outperforms a nonlinear one. The simulation results of Singh and Woolhiser provide a persuasive reason for using linear models; however, experience using actual data suggests that in many circumstances nonlinear models provide improved performance, presumably because amplification of errors by nonlinear models is less deleterious than the use of a linear model to represent the nonlinear rainfall-runoff process in these situations. Weather radar's shortcoming in not always providing reliable quantitative measurements of rainfall (Collier et al, 1983), and the need for robust flood forecasts, may mean that linear models might be preferable in some cases.

Effect of using lumped, areal average, rainfall

Basin average rainfall estimated by a single raingauge measurement or as an average of measurements from a small number of raingauges will have a greater variance than rainfall averaged over an infinite number of points within the basin. This error associated with raingauge network derived estimates of basin average rainfall may be termed a space-sampling error and is a major cause of bias in runoff prediction (Troutman, 1982, 1983). Its effect is to tend to make the rainfall-runoff model overpredict large events and underpredict small events. In practice this bias is compensated for by calibrating the rainfall-runoff model by least squares using the raingauge network derived areal estimates of rainfall. However, if a model is calibrated in this way, and then used operationally for flood forecasting using radar-derived areal average rainfalls, there will be a tendency to underpredict large events and overpredict small events, on account of the lesser variability of the radar-derived estimate. This serves to emphasise the importance of calibrating rainfall-runoff models using the data source which is to be used in real-time. In the event of a weather radar malfunctioning, it would be desirable to switch to the use of telemetering raingauges and a rainfall-runoff model specifically calibrated using data from these gauges. Ideally a flood warning system should accommodate a range of model calibrations appropriate to each possible configuration of raingauge and radar measurements of rainfall, thereby catering for all possible scenarios of data availability.

THE POTENTIAL VALUE OF WEATHER RADAR DATA

Moore (1977) investigated the effect of using several raingauges located in and around a basin as inputs to a multiple-input transfer function model; data from up to six raingauges in the vicinity of the small (33.9 km^2) Hirnant basin in North Wales, were employed. The inclusion of more than two gauges, either as separate inputs or as a single average value, failed to improve forecasts of hourly flows. It was argued that a gauge, or set of gauges, should not be chosen for use in flood forecasting in terms of how well it estimates the basin average rainfall, but rather on the strength of its association with observed river flows. Siting of a single gauge in the vicinity of the contributing area of storm runoff (for example, located near the basin outlet) could be superior for flood peak forecasting than a dense network designed to obtain a good estimate of the basin average rainfall. This argument can be forwarded to suggest that only radar grid square estimates of rainfall located in the area contributing to the flood hydrograph rising limb and peak be used for flood forecasting. Observed flows may be used in a forecast updating algorithm to compensate for forecast errors on the falling limb, where flows originate from rain falling on more distant parts of the basin. Research leading to a prescription for rainfall measurement requirements for real-time flood forecasting systems, which takes into account the complementary role of radar-derived and gauge estimates of rainfall, is seen as a need for the future.

Storm movement

Weather radar data may be of most value when storm movement across a basin exerts a strong influence on the form of the resulting flood hydrograph. Hamlin (1983) presents the results of Bramley's work on simulating a storm hydrograph by moving a fictitious storm cell across a basin. The effect of sampling rainfall from the storm cell by a varying number of point raingauges is investigated and shown to result in large errors in the timing and volume of the hydrograph peak. In such situations, the rainfall pattern obtained from weather radar could be very useful in ameliorating the errors incurred by inadequate sampling of the rainfall field by a sparse raingauge network. However, this would depend on the availability of a distributed rainfall-runoff model to fully utilise the weather radar data, and on the accuracy of the weather radar data. Ngirane-Katashaya and Wheater (1985) also demonstrate the importance of storm movement on flood peak generation through simulation experiments on a synthetic urban catchment. Niemczynowicz (1984), in a comprehensive investigation of the areal and dynamic properties of rainfall and its influence on runoff production, illustrates the importance of catchment shape and orientation relative to the direction of storm movement: greater peak discharges result from long, narrow basins orientated in the prevailing storm direction. Weather radar data may therefore be expected to be of greatest value on such basins, if used as input to a model which is distributed in form; the development of such models will be discussed later.

DISTRIBUTED MODELS FOR REAL-TIME FLOOD FORECASTING USING GRID SQUARE WEATHER RADAR DATA

With the increasing availability of radar-derived rainfall data for use in operational flood forecasting, the hydrologist has an obligation to make the best use of such data through the development of distributed models capable of real-time implementation. Such models would have the potential to overcome the poor performance of lumped rainfall-runoff models in situations where spatial non-uniformity of rainfall and storm movement are important, as previously discussed. Whilst physics-based models (Abbott et al, 1978; Morris, 1980) are distributed in three dimensions, with changes in water content with depth being modelled through solution of the equations of Richards and Boussinesq, there is scope for development of simple distributed models which lump the depth dimension, for example into soil- and ground-water components; these models should be capable of implementation in real-time on a continuous basis whilst making better use of the distributed radar-derived rainfall data. The most common approach is to sub-divide a basin into sub-catchments and channel segments, and use lumped rainfall-runoff models to forecast sub-catchment flows. This approach was used as part of the Dee Weather Radar Project (Central Water Planning Unit, 1977). Figure 1 shows how the subcatchments were approximated by the 2 km radar grid in order to derive subcatchment average rainfalls from the radar grid square values. Considerable loss of information on spatial variability may be incurred depending on the relative magnitudes of subcatchments and radar grid squares, and the degree of rainfall variability experienced over the subcatchment. A simple, alternative scheme, would be to represent each radar grid square by some form of transfer function or nonlinear storage model, and obtain the basin flow response by combining their individual responses, after being shifted in time in relation to their distance from the basin outlet (possibly also including slope information to better approximate time of travel). A similar scheme could be used to forecast lateral inflow to a channel flow routing model. An example of where a grid square model has been

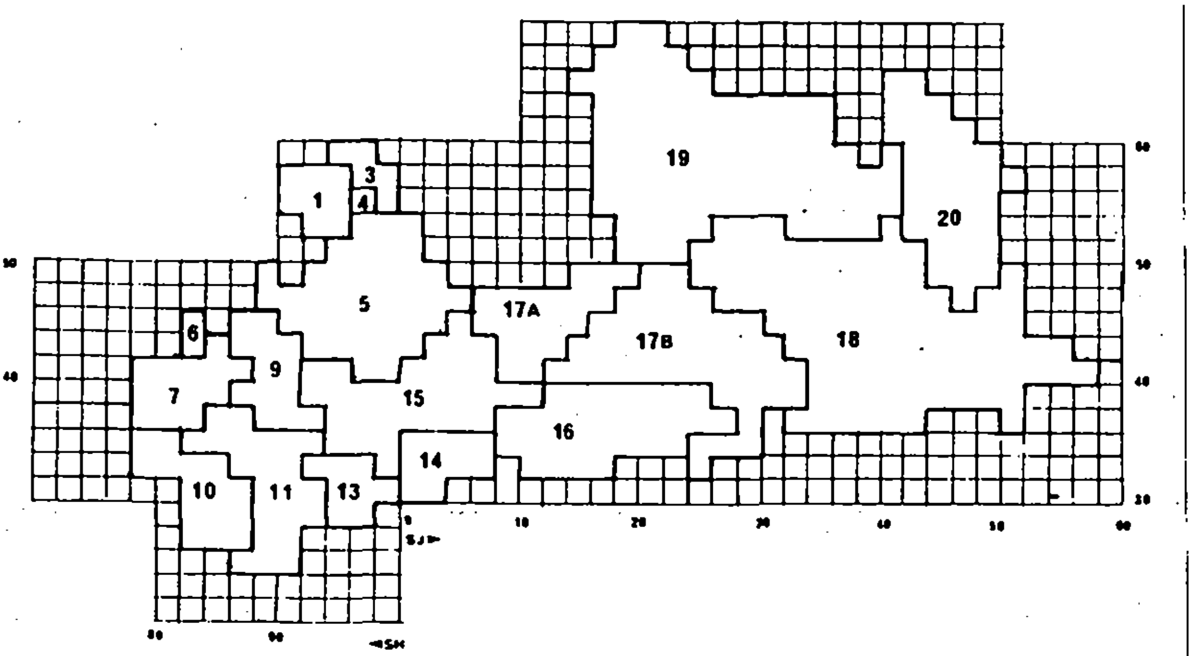


Figure 1 Grid square representation of the River Dee subcatchments used for radar purposes (each grid is 4 km^2 in area)

used with radar data is presented by Anderl et al (1976): an effective rainfall separation and time shift at each grid square is followed by routing of the combined flows through two unequal reservoirs. This model is shown to provide more accurate forecasts with radar data as input than the use of spatially interpolated estimates, derived using data from a regular raingauge network. The value of adopting a more distributed model would, of course, depend on the number of radar grid squares encompassed by the basin, and might be expected to be of greatest value in parts of the world where flood forecasts are required for larger basins than those found in the United Kingdom.

A probability-distributed model of rainfall and runoff production for use with weather radar data

Instead of developing a geometrically-distributed model of basin runoff, an attractive compromise would be to utilise the information on spatial variability of rainfall provided by weather radar to define a spatial distribution function of rainfall, and to incorporate this into a rainfall-runoff model. Thus the mean rainfall used in a lumped model, is replaced by a spatial distribution of rainfall, characterised not only by its mean but by the form of variability about this mean. Whilst the geometric pattern of rainfall over space is discarded in this compromise approach, information on the frequency of occurrence of rainfall of given magnitudes over the catchment is retained. We will now discuss how this spatial frequency information may be incorporated into a rainfall-runoff model.

Consider that runoff production at a point is controlled by a simple excess mechanism, so that rainfall above a given value becomes runoff. This excess mechanism may be due to the soil not allowing water to enter the soil above some maximum rate (the infiltration capacity), or due to the soil having a limited capacity to store water (the storage capacity). Mathematically this may be represented by

$$q = \begin{cases} p - c & p > c \\ 0 & p \leq c \end{cases} \quad (1)$$

where c is the threshold capacity, p the rainfall, and q the runoff. The spatial variation of rainfall and threshold capacity over the basin may be considered as a bivariate probability density function, $f(p,c)$, such that $f(p,c)dpdc$ denotes the probability of rainfall and capacity at any point in the basin being in the range $(p,p+dc)$ and $(c,c+dc)$. It is reasonable to assume that p and c are independent random variables with density functions $f_p(p)$ and $f_C(c)$, so that $f(p,c) = f_P(p)f_C(c)$; $\bar{p}$ and $\bar{c}$ will be used to denote the mean rainfall (the expected value of p) and the mean capacity respectively. According to the point description of runoff production specified by Eq. (1) it follows that runoff production from the entire basin will be given by

$$Q = \int_0^\infty \int_c^\infty (p-c)f_P(p)f_C(c)dpdc \ . \quad (2)$$

Some algebra leads to the result

$$Q = \bar{p} - \int_0^\infty (1-F_P(p))(1-F_C(p))dp \ , \quad (3)$$

where $F_P(p)$ is the distribution function of rainfall, indicating the proportion of the basin where rainfall is less than p, and $F_C(p)$ is the distribution function of capacity, indicating the proportion of the basin where the capacity of the soil to take up water is less than p. For ease of illustration, we will assume the density functions to be exponential, so that

$$F_P(p) = 1 - \exp(-p/\bar{p}) \tag{4a}$$

$$F_C(p) = 1 - \exp(-p/\bar{c}) \ . \tag{4b}$$

Then

$$Q = \bar{p} - \int_0^\infty \exp\left\{-p\left(\frac{1}{\bar{p}} + \frac{1}{\bar{c}}\right)\right\} dp \tag{5}$$

which leads to the simple relation

$$Q = \frac{\bar{p}^2}{\bar{p}+\bar{c}} \ . \tag{6}$$

This result shows how basin runoff changes with mean rainfall for given mean soil absorption capacities under the assumption that the variation of rainfall and capacity over the basin is exponential. Figure 2 shows the form of this relation, and in particular how basin runoff is increased when rainfall and capacity is no longer assumed constant over the basin (when $Q = \bar{p}-\bar{c}$) but vary exponentially (when $Q = \bar{p}^2/(\bar{p}+\bar{c})$). The approach may be developed further to give a new type of rainfall-runoff model, either based on a storage capacity excess mechanism generating saturation overland flow or on an infiltration capacity excess mechanism producing Hortonian overland flow, and incorporating groundwater and channel translation components. The inclusion of rainfall variability into the above model development represents a new advance on the probability-distributed rainfall-runoff models recently reviewed and extended by the author (Moore, 1985).

This new approach would utilise grid values of radar-derived rainfall to identify a suitable parametric form for the density function, $f_P(p)$, and at each time frame would use the grid data to estimate the function's parameter(s). For example, the average of the grid square values would be used to estimate the mean basin rainfall, $\bar{p}$, specifying the exponential density, $f_P(p) = \bar{p}^{-1} \exp(-p/\bar{p})$; a new estimate of $\bar{p}$ would be obtained at each time frame in order to calculate basin runoff. Histograms of hourly rainfall amounts, derived from radar measurements presented on a 12 x 10 radar grid (5 km square grid) located north-west of Birmingham airport and extending over an area of 3,000 km^2, are presented in Figure 3. These suggest that a simple exponential density function may indeed be adequate. A theoretical justification for rain falling on equally divided small cell regions having an exponential distribution is given by Matsubayashi et al (1984), and empirical confirmatory evidence is provided using a dense network of raingauges in the vicinity of Nagoya City, Japan. As the size of the cell increases, the distribution is shown to change to gamma and then Gaussian form.

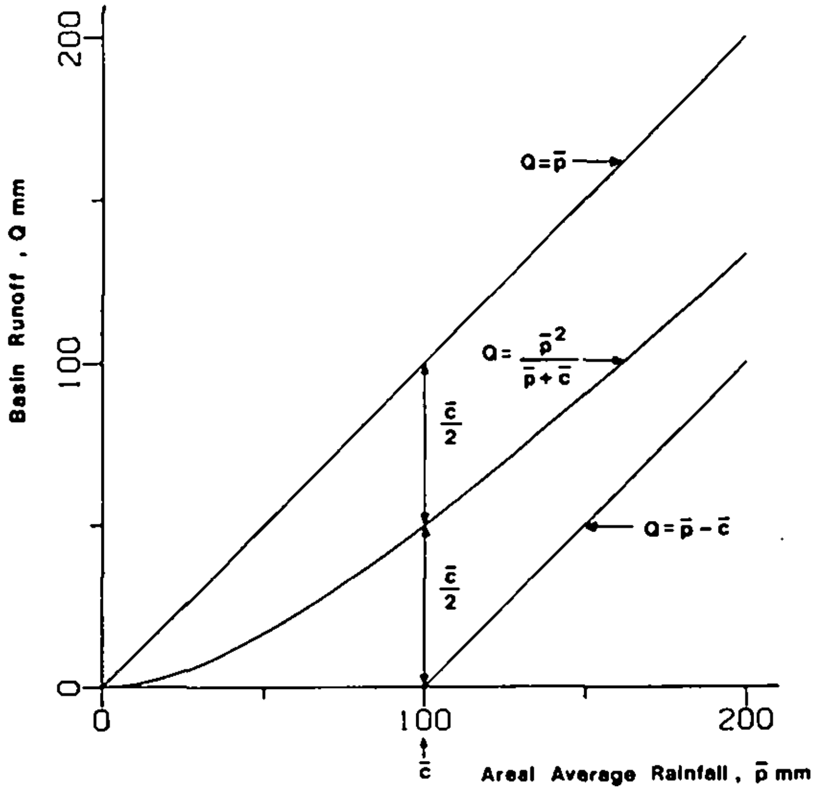


Figure 2 Rainfall-runoff relationship for the probability-distributed model of rainfall and runoff production

(a) 11.00 hrs

LH ENDPOINT	COUNT	
0.	5	*****
2.5	9	*********
5.0	8	********
7.5	3	***
10.0	6	******
12.5	4	****
15.0	12	************
17.5	6	******
20.0	3	***
22.5	5	*****
25.0	0	
27.5	1	*
30.0	2	**
32.5	1	*
35.0	0	
37.5	0	
40.0	0	
42.5	0	
45.0	1	*

(b) 12.00 hrs

LH ENDPOINT	COUNT	
0.	61	*******************************
40.	19	*********
80.	21	**********
120.	17	********
160.	11	*****
200.	15	*******
240.	3	*
280.	7	***
320.	4	**
360.	4	**
400.	3	*
440.	1	
480.	0	
520.	1	

(c) 13.00 hrs

LH ENDPOINT	COUNT	
0.	99	**
15.	39	********************
30.	32	****************
45.	12	******
60.	6	***
75.	4	**
90.	5	**
105.	1	
120.	4	**
135.	0	
150.	3	*
165.	1	
180.	1	
195.	0	
210.	2	*

(d) 14.00 hrs

LH ENDPOINT	COUNT	
0.	7	*******
50.	19	*******************
100.	39	***************************************
150.	27	***************************
200.	23	***********************
250.	14	**************
300.	18	******************
350.	15	***************
400.	17	*****************
450.	11	***********
500.	16	****************
550.	9	*********
600.	5	*****
650.	5	*****
700.	6	******
750.	2	**
800.	3	***
850.	1	*

Figure 3 Histograms of hourly rainfall amounts (units are 0.1 mm) derived from a 12 x 10 radar grid (5 km square grid) north-west of Birmingham airport on 14 July 1982

The probability-distributed model of rainfall and soil water capacity is seen as presenting a novel way of making greater use of spatially distributed weather radar data without resorting to the complexity of a geometrically distributed rainfall-runoff model. However, its practical utility remains to be assessed.

VALUE OF RADAR RAINFALL DATA IN CHANNEL FLOOD ROUTING MODELS

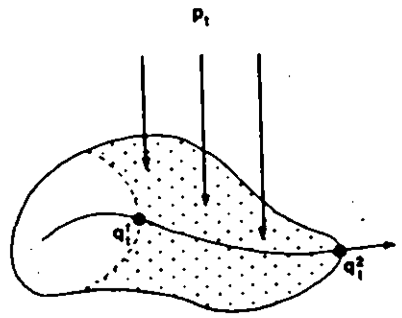
In circumstances where flood warning is to be provided at a point downstream of two or more streamflow gauging stations, then the flood forecasting model will usually consist of both channel routing and rainfall-runoff components. In Consider the problem of constructing a flow forecasting strategy for the simple river basin depicted in Figure 15.4(a). The straightforward approach would be to construct a model relating the downstream flow at time t, q_t^2, to the sum of two components, one attributed to the influence of the upstream flow, q_t^1, and the other due to lateral inflow from the intermediate catchment area; Figure 15.4(b) presents a schematic of the model structure where rainfall, p_t, over the lateral inflow area is assumed to be derived from a sparse raingauge network. The component of the flow forecast deriving from the influence of the lateral inflow will be expected to account for most of the errors in the total forecast because of errors in the gauge-derived areal rainfall estimate, and the greater difficulty of modelling the rainfall-runoff process compared to modelling the channel flow routing process. Indeed, an improved forecast may result from omission of the rainfall information altogether, using instead the upstream flow, q_t^1, as input to a channel flow routing model which does not preserve continuity, but amplifies the upstream flow volume to that of the downstream flow to be forecast. This would be done in the belief that upstream flow is more representative of flow from the ungauged area contributing lateral inflow than forecasts from a rainfall-runoff model using error-corrupted rainfallmeasurements over the ungauged area as input.

Even if the forecast from a model which includes the raingauge data is superior in an average sense, it may not be preferred on account of its lack of "robustness". Here we mean that a model lacks robustness if it can give rise occasionally to very spurious forecasts on account of errors, in this case due to the use of point gauge measurements to estimate areal rainfall. In such circumstances, radar data may be expected to provide more robust forecasts from rainfall-runoff models than would be obtained from a sparse raingauge network, especially in areas experiencing high spatial variability in rainfall. An argument based on lack of robustness has been used to exclude raingauge measurements from a procedure developed to forecast inflow to a reservoir located in the tropics,where rainfall is spatially highly variable and raingauges are few; forecasts were required to be robust since they were to assist in the control of a reservoir in order to mitigate flooding downstream. In such circumstances radar-derived rainfall data may be expected to provide more robust information on lateral inflow variation than can be provided by at-a-point raingauge measurements.

THE ROLE OF UPDATING METHODS IN COMPENSATING FOR RAINFALL ERRORS

The degradation of rainfall-runoff model performance by error-corrupted rainfall input data may be compensated for in real-time through updating techniques which incorporate current measurements of flow at the forecast location. Updating may be accomplished by (i) error prediction, where the temporal persistence of model errors is used to predict future errors, (ii) parameter adjustment, and (iii)

(a) Basin form



(b) Model structure

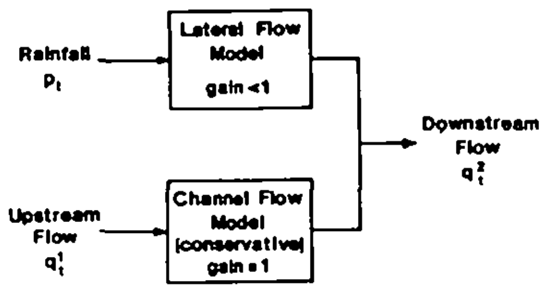


Figure 4 A flood forecasting model incorporating a continuity-preserving channel flow routing model and a rainfall-lateral inflow model

state adjustment, where corrections are made to the water content of internal storages to achieve accordance with observed flows. Reviews of these techniques are presented in Reed (1984) and Moore (1983). Error prediction may now be regarded as an established technique which is easy to implement (Moore, 1982; Jones and Moore, 1980); however, its benefit is often least in the vicinity of the hydrograph peak where model errors display least temporal persistence. Parameter adjustment, accomplished usually by techniques based on the Kalman filter (Jazwinski, 1970), appears to be a less attractive option for real-time application since parameter variation usually reflects an inadequate model structure, which can be improcved by off-line studies. State adjustment is seen as a promising area for further research, and is of the most relevance to the problem of error-corrupted rainfall measurements. The effect of errors in rainfall accumulate as errors in the water contents of stores making up a conceptual rainfall-runoff model, and in turn contribute to the errors incurred in forecasting the flood hydrograph through incorrect partitioning of rainfall exact solution for linear systems even when the random variations may be non-Gaussian, only approximate solutions may be obtained for nonlinear conceptual rainfall-runoff models. There is considerable scope for developing empirical state updating schemes, which exploit the hydrologist's understanding of the physical mechanisms operating. These schemes use the model error, ε, to adjust the set of model store contents (the state variables): for example, the soil water store content, S_1, and the groundwater store content, S_2. The adjustment chosen might be of the familiar Kalman filter form

$$S_i^* = S_i + K_i \varepsilon \quad i=1,2, \tag{7}$$

but the gains K_1 and K_2 would be derived empirically through optimisation. Dependence of K_1 and K_2 on measured discharge or on the model flow components could also be incorporated in physically sensible ways into this empirical state updating scheme. Whilst not removing the need for accurate rainfall measurements up to the present and forecasts of rainfall in the future, state adjustment provides a mechanism for compensating for the effect of past error-corrupted rainfalls on the internal states of the model which affect the important separation of rainfall into its storm and baseflow runoff components.

THE HYDROLOGICAL USE OF RADAR-DERIVED FORECASTS OF RAINFALL

Perhaps the most serious shortcoming of rainfall-runoff models for flood forecasting is their dependence on the availability of rainfall forecasts in order to forecast flows at lead times beyond the natural time lag of the catchment. Radar's ability to portray the pattern of rainfall over space and to allow the movement and the development of the pattern to be monitored over time give rise to high expectations of radar's value for rainfall forecasting. Methods which have been developed for rainfall forecasting using weather radar are largely based on displacement of the radar-derived grid square estimates so as to maximise some measure of association with values obtained at subsequent time frames; examples are provided by Austin and Bellon (1974) in the USA, by Hill et al (1977) in the UK, and Yoshino (1985) in Japan. The hydrologist still awaits refinements to these techniques, studies evaluating their worth for flood warning, and their provision in real-time for use in operational flood warning and reservoir control schemes.

EVALUATING RADAR-DERIVED RAINFALL FOR FLOOD FORECASTING

Having discussed some ways in which weather radar might be more effectively used for flood forecasting, a re-evaluation of the benefit of radar relative to conventional raingauge networks is called for which incorporate these ideas. An evaluation framework for assessing the value of radar-derived rainfall data for flood forecasting may take two forms. The indirect approach is to assess the weather radar's ability to estimate areal average rainfall, a quantity often stated as a requirement for data input to lumped rainfall-runoff models. An assessment of this type is problematic due to the lack of "truth data". The expensive solution of comparing radar estimates of areal rainfall with estimates derived from a special dense network of recording raingauges has been used in the past, for example as part of the Dee Weather Radar Project (Central Water Planning Unit, 1977; Harrold et al, 1974). A more satisfactory evaluation in terms of radar's value specifically for flood forecasting would be based on a direct assessment of the forecasting performance it provides relative to that obtained from the use of data from recording raingauge networks of differing density and configuration. Given the earlier discussion of the effect of rainfall input errors on rainfall-runoff model performance, it would clearly be necessary to calibrate models using both sources of data in order to achieve a fair comparison. Special consideration would also need to be given to the rainfall-runoff model structures to be used since these would influence the final outcome: in particular, models which fully exploit the spatial nature of radar-derived rainfall data should be included. To achieve a fair comparison with data derived from a raingauge network, techniques of spatial interpolation using raingauge data would need to be employed in order to provide data input to grid square distributed models used in the evaluation (Anderl et al, 1976; Bastin et al, 1984). For the results of the evaluation to have any credibility, a reasonably large number of flood events would be needed for calibration, together with a further set of events for use in an independent model evaluation. The evaluation should also be carried out for a range of catchments of differing hydrological character, in order to construct guidelines for weather radar's utility across a range of hydrological situations. In particular, the intense and localised nature of rainfall in semi-arid regions of the world provides a strong a priori argument in favour of weather radar, as opposed to gauge-based, rainfall measuring networks for use in flood forecasting, but this has yet to be demonstrated in practice. At present no rigorous direct evaluation across a range of hydrological environments has been made, and indeed the data base to support such a comparison is still not available. Such an evaluation is clearly a crucial requirement for the future.

CONCLUSION

Collier (1984) provides a cogent summary of the present state-of-the-art in the use of radar rainfall data for flood forecasting. He states that "..it is still not clear whether the accuracy quoted in the literature can be reproduced consistently in a fully operational system, or indeed whether that accuracy is acceptable for real-time flood forecasting. There have been few, if any, reports describing radar systems which make quantitative measurements continuously (24 hours per day) over a long period during which data have been supplied direct to hydrological and meteorological users." This points to a future requirement for a more extensive evaluation of flood forecasting performance based on radar rainfall data and the need for continuous intra-storm data sets on which to base such an appraisal. However there is also a requirement for the hydrologist to develop real-time flood forecasting techniques which make full use of the spatially distributed picture of rainfall that radar provides, and which compensate for its variable precision. The present paper has made some suggestions as to how this development might proceed.

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RISK ASSESSMENT AND DROUGHT MANAGEMENT IN THE THAMES BASIN

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ABSTRACT

A risk assessment procedure is described for use in managing a system of pumped-storage reservoirs in the Thames basin during a drought. Historical daily rainfall sequences are used as equi-probable scenarios of future rainfall. These are transformed to flow, reservoir level, and demand restriction sequences through the use of rainfall-runoff and water resource system models. The risk assessment information required is then obtained through a statistical analysis of these sequences. A novel technique is presented for incorporating monthly rainfall forecasts, presented as probabilities of rainfall being above average, average, or below average, into the risk assessment scheme. Information on current hydrological conditions is incorporated in the procedure through the use of recently observed natural flows to adjust the internal state variables of a conceptual rainfall-runoff model to achieve agreement between observed and model flow. The overall procedure is accommodated within a decision support system for drought management which is implemented on a microcomputer and makes extensive use of interactive menus, forms and colour graphic displays. A key feature of the system is the maintenance of an up-to-date archive of hydrometric data: this is achieved through a real-time communication link with a second computer dedicated to real-time data acquisition via telemetry. Monitoring the reliability of the water resource system during droughts is made a quick and easy task, and the effect of a change in the operating policy on system reliability can be readily assessed. The information obtained provides valuable support for tactical decision-making within the overall long-term operating strategy.

INTRODUCTION

About 58% of water supply needs in the Thames basin derive from pumped-storage reservoirs which are replenished entirely by river abstraction, apart from rainfall inputs, net of evaporation, over the reservoired areas. The ability of these reservoirs to meet supply needs depends primarily on variable river flow, given fixed system constraints in the form of abstraction licences, reservoir and pump capacities, etc. This paper outlines a procedure for continuously monitoring the reliability of the system during periods of drought. The procedure takes the form of a decision support system designed so that the water resource manager can explore the effect of alternative decisions on resource reliability over the

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forthcoming days, weeks and months.

WATER RESOURCE SYSTEM MODELS

The location of the pumped-storage reservoirs in the Thames basin is indicated in Figure 1. For water resource modelling purposes the reservoirs are viewed as two separate systems, namely the London reservoir system and Farmoor reservoir. The latter is located in the upper part of the basin near Oxford, and has an operating capacity of 13,800 Ml supplying an average daily demand of 90 Ml. More important is the London system of reservoirs located in two main groups along the lower Thames and Lee valleys: these have a combined operating capacity of 206,400 Ml supplying an average daily demand of 1,800 Ml. Simplified system diagrams for the two reservoir systems are shown in Figure 2. The London system, although made up of about 18 reservoirs fed via about 12 river intakes, is modelled as an aggregated system of two reservoirs replenished via two notional abstraction points on the Thames and Lee.

A complex set of constraints and operating rules define the behaviour of the reservoirs and these have been incorporated in the water resource system models for the two systems. Account is taken of seasonal demand profiles, demand restriction rules imposed during reservoir drawdown, constraints in the form of abstraction licences, residual flow requirements, pump and reservoir capacities, and rules to apportion water between the two London reservoir groups.

RISK ASSESSMENT AND RELIABILITY STANDARDS

A key feature of the operating policy is a set of demand restriction curves which are applied during drought periods as reservoir storage becomes progressively more depleted (Figure 3). The restriction curves have been derived on the basis of achieving a target level of service specified in terms of the frequency with which restrictions of differing severity can be tolerated over the long-term. This target level of service is summarised in Table 1. It is clear that, in the course of tactical decision-making on a day-to-day basis, it will be often the case that the apparent risk of having to introduce a demand restriction will exceed the target level of service. When this apparent risk becomes high enough it would be appropriate for the responsible water resource manager to take special executive action. The association between this critical level of risk and the target level of service is not straightforward: experience in operating the risk assessment procedure during drought periods is required. It might be appropriate, for example, to take action if the assessed risk of having to introduce Restriction Level 4 within two months exceeds, say 50%. As an alternative, the apparent risk of having to introduce demand restrictions may influence the choice at a tactical level,

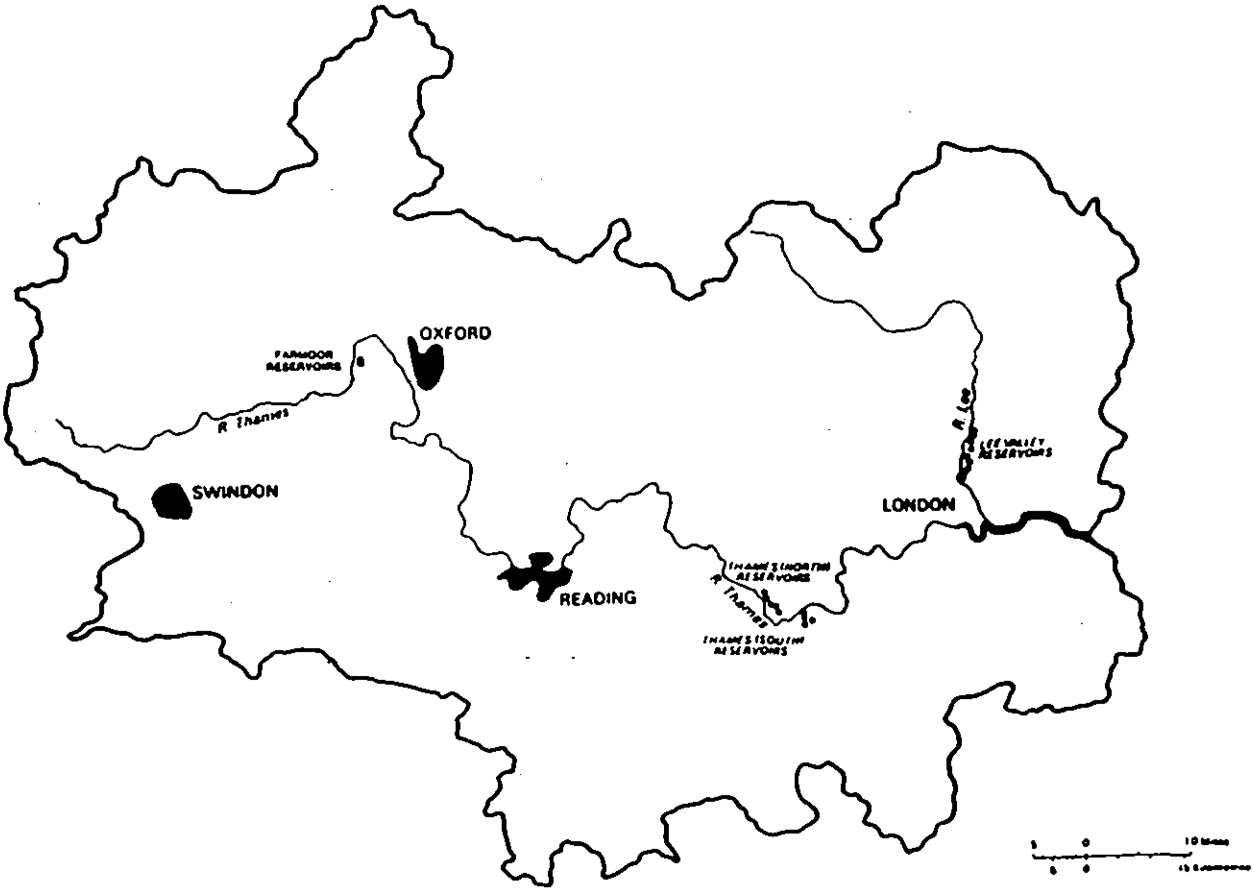
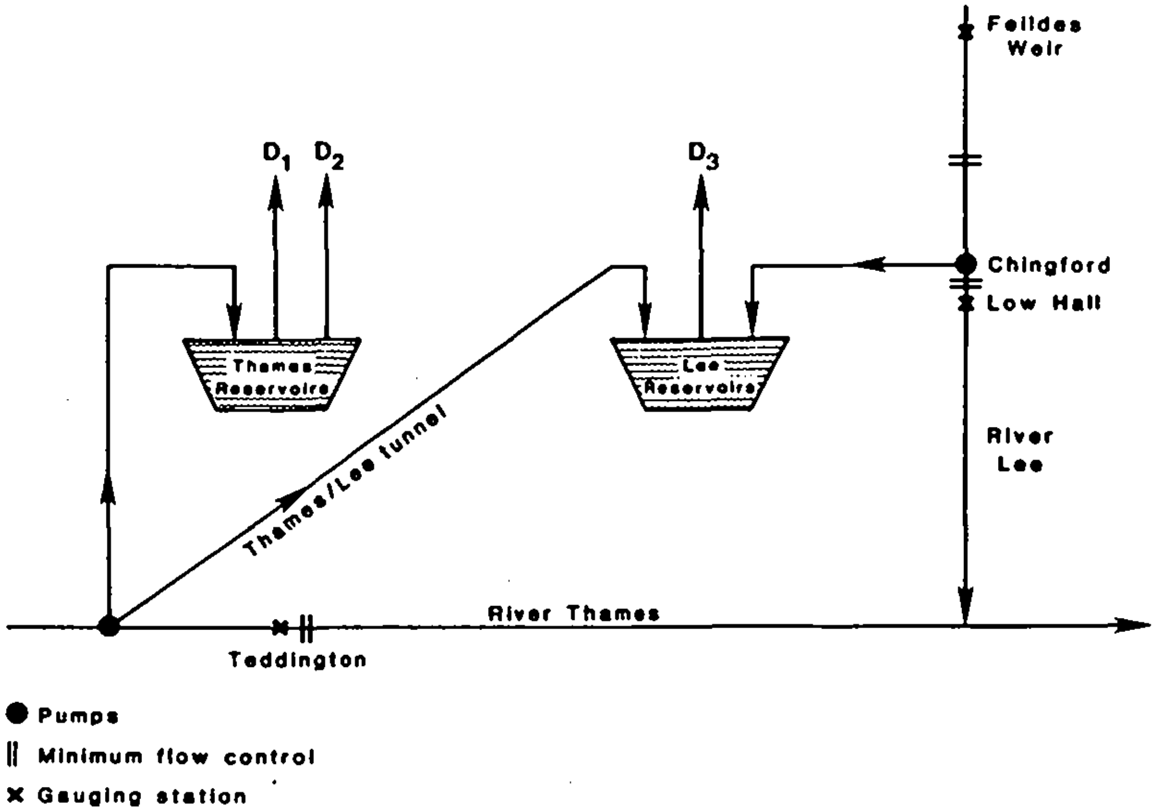


Figure 1 Location of pumped-storage reservoirs in the Thames basin

(a) London reservoir system



(b) Farmoor reservoir system

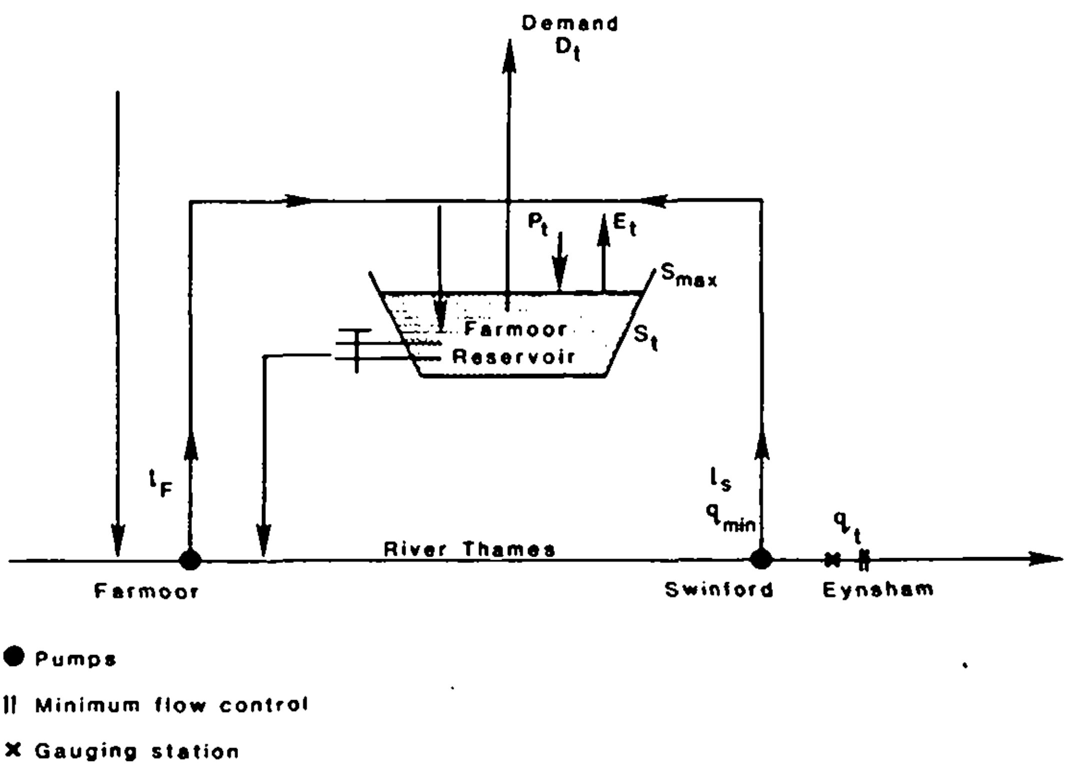


Figure 2 System diagrams for the Thames basin reservoirs

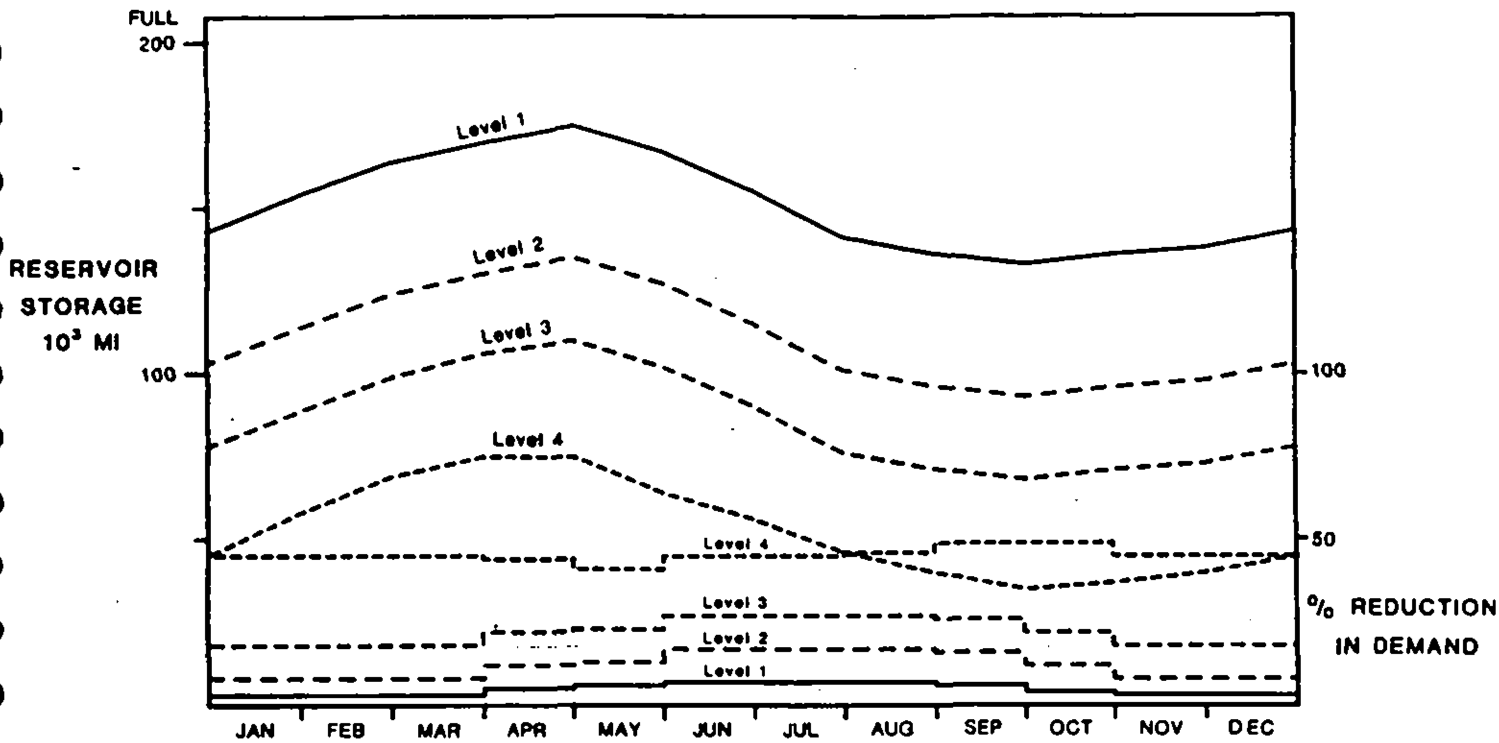


Figure 3 Demand restriction curves and the corresponding demand reduction curves for the London reservoir system

Table 1 Demand restriction levels and reliability standards

Restriction Level	Action	Maximum permissible risk of occurrence in any one year %
1	Hosepipe ban Initial publicity campaign	17
2	Voluntary restrictions on inessential use Reduction of pressure in the distribution system	5
3	Implementation of Drought Act 1976 restrictions banning inessential use Some further pressure reductions	2
4	Major cuts in supply on a rota basis, or use of standpipes	1

between cost-saving and water conservation measures, either formally or informally.

RISK ASSESSMENT PROCEDURE

A summary of the risk assessment procedure developed for tactical management of the Thames basin surface water resources is shown in Figure 4. The essential ingredient of the scheme is the use of historical daily rainfall sequences to represent equi-probable scenarios of future rainfall: these are transformed to daily flows using a rainfall-runoff model and in turn to reservoir levels through a water resource system simulation model. A statistical analysis of reservoir levels and associated demand restrictions imposed then provides the risk assessment information required. If this shows a high risk of imposing demand restrictions then the water resource manager can respond by departing from the long-term operating strategy in some way, for example in reducing demands by seeking alternative sources or in seeking legal sanction to relax statutory controls on abstraction. The way in which the level of service provided is affected by different decision options can be evaluated by incorporating them in the water resource system model and repeating the risk assessment. Thus, the procedure provides support for a particular decision when a number of management options are available.

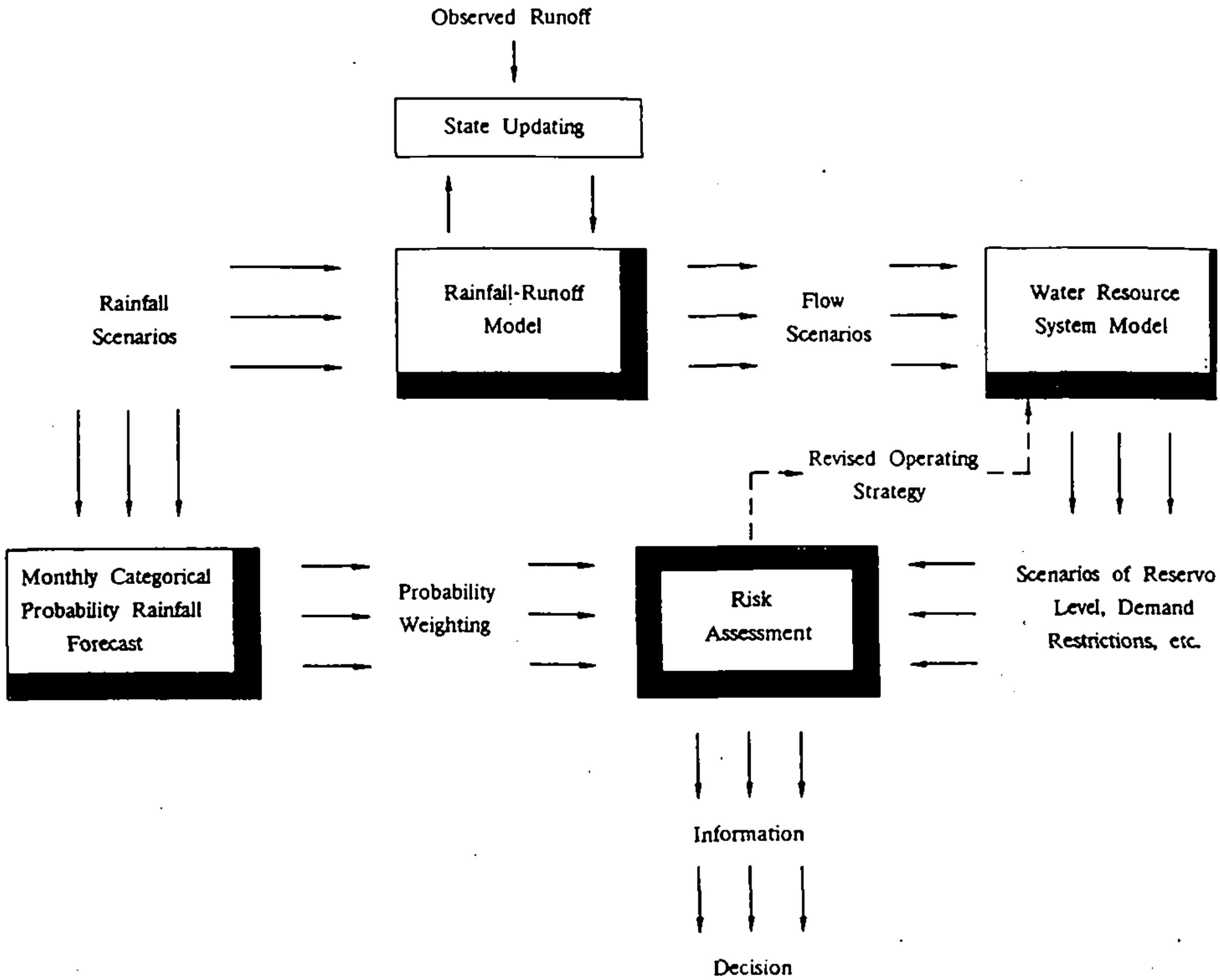


Figure 4 The risk assessment procedure

USE OF HISTORICAL RAINFALL SEQUENCES

Risk assessments based on the direct use of historical flow sequences in the simulation model of the water resource system would be unsatisfactory for two reasons: first the shorter records available for flow as opposed to rainfall, and second the substantial change in hydrological response due to the impact of man in the highly urbanised Thames basin. Of course, the use of flows in critical drought years forms a valuable complement to a probability-based risk assessment, and is incorporated as an option within the decision support system. The option to use stochastic models of catchment rainfall was not adopted since there exist long historical records of rainfall available for the Thames basin; further, it would be difficult to meet the potential requirement for daily areal average rainfall models for three sub-basins of the Thames rather than for a simpler single point model. Historical records of rainfall from 1890 to the present are used in the procedure to give up to 98 equi-probable sequences of future rainfall for the forecast period starting from the current day: for example a 3 month forecast made on 1 April 1987 would use the 97 rainfall sequences available for the months April, May and June.

INCORPORATION OF MONTHLY RAINFALL FORECASTS

The basic principle underlying the risk assessment procedure is that each rainfall scenario extracted from the historical record may be used to represent an equi-probable sequence of future rainfall. Flow and reservoir level sequences derived from such sequences through transformations in the form of rainfall-runoff and water resource system models may in turn be regarded as equi-probable. However, if additional information is available which indicates that a rainfall sequence for a particular past year is more likely to resemble rainfall over the forecast period, then such information could be incorporated by giving the sequence greater weight when estimating risk probabilities. Such information is available in the form of monthly rainfall forecasts provided by the UK Meteorological Office. These forecasts are expressed in terms of probabilities that rainfall will be "Below Average", "Average" or "Above Average" for the forthcoming month. Each category represents one-third of all possible rainfall sequences. The basis of these categorical probability rainfall forecasts is described in detail by Maryon and Storey (1985) and Folland and Woodcock (1986); essentially, the forecast procedure involves the application of multivariate analysis techniques to mean surface pressure anomalies and sea surface temperatures over the Europe and North Atlantic area.

A simple use of these probabilities in the risk assessment procedure is as follows:-

(1) use the historical record to determine the rainfall amount defining the two

category boundaries for the month concerned;

(2) identify for each year of the historical record the category to which the monthly rainfall belongs;

(3) to each of the n years assign a weight, w_i, calculated as the forecast probability of rainfall falling in the category divided by the sum of these probabilities for every year of record;

(4) rank the n reservoir levels on a particular day of the forecast period derived from each rainfall sequence, keeping the weights attached;

(5) sequentially sum the weights to obtain the probability of exceedence of the r'th ranked storage, S_r, as $p_r = \sum_{i=1}^{r} w_i$, so that $\{p_i\}$, i=1,2,..., n defines an empirical distribution function of storage for the day concerned;

(6) calculate the storage levels having specified risks of not being reached on that day by interpolation of the empirical distribution function.

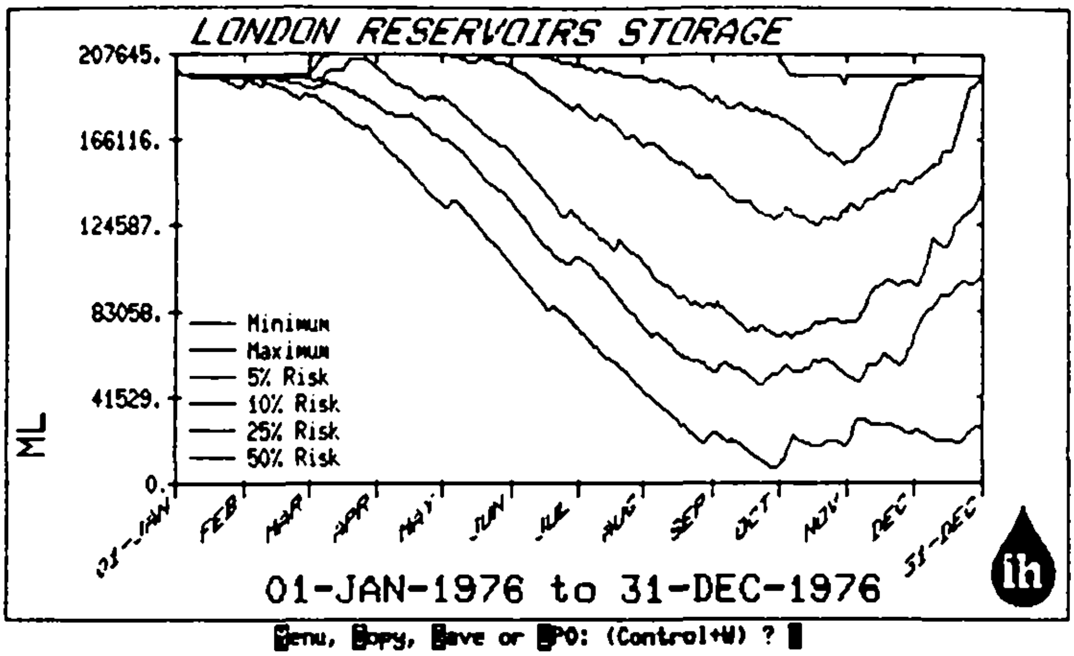
Steps (4), (5) and (6) are repeated for each day of the forecast period to produce the final risk assessment information shown in Figure 5.

In practice a refinement of this procedure is used to overcome the possibility of applying very different weights to historical rainfall sequences which, although they have similar monthly totals for the month of the rainfall forecast, fall either side of a category boundary. A piecewise linear smoothing function has been developed and Figure 6 illustrates its application to a range of categorical probability forecasts. Details of the mathematical definition of the function are presented by Moore et al. (1986a), but its main feature is that it preserves the forecast probability of rainfall falling within each of the three categories. A plotting position formula applied to the ranked historical rainfalls for the month concerned is used to enter the function and return weights to be attached to each year.

RISK ESTIMATES

Figures 5 (a) and (b) illustrate risk estimates made for the London total reservoir storage during the drought of 1976 according to the procedure described above, first assuming scenarios are equi-probable and second using a rainfall forecast that there is a probability of January 1976 rainfall being 60% below average, 30% average, and 10% above average. This example is intended for the purpose of illustration only, and more usually the rainfall forecast would be less 'strong' and the forecast origin would be during the summer drawdown period and not on 1 January. The 50% risk level corresponds to the median forecast or expected state of reservoir storage levels and the two extreme lines are envelope curves drawn through

(a) Equi-probable scenarios



(b) Monthly rainfall forecast weighted scenarios

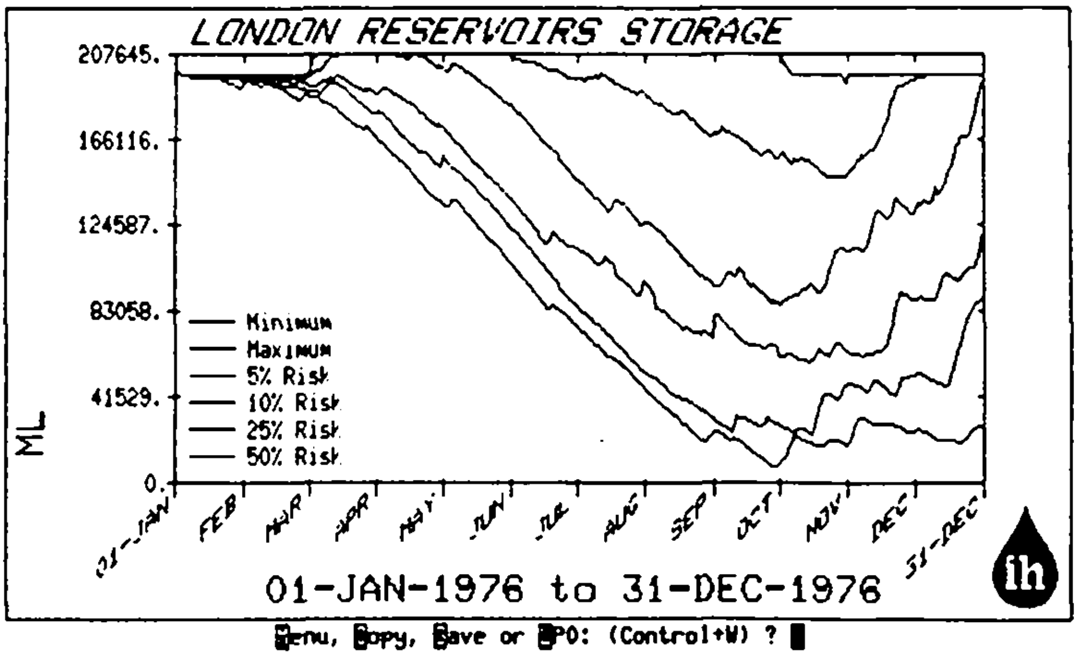


Figure 5 Risk assessment of the London reservoir system for the drought of 1976

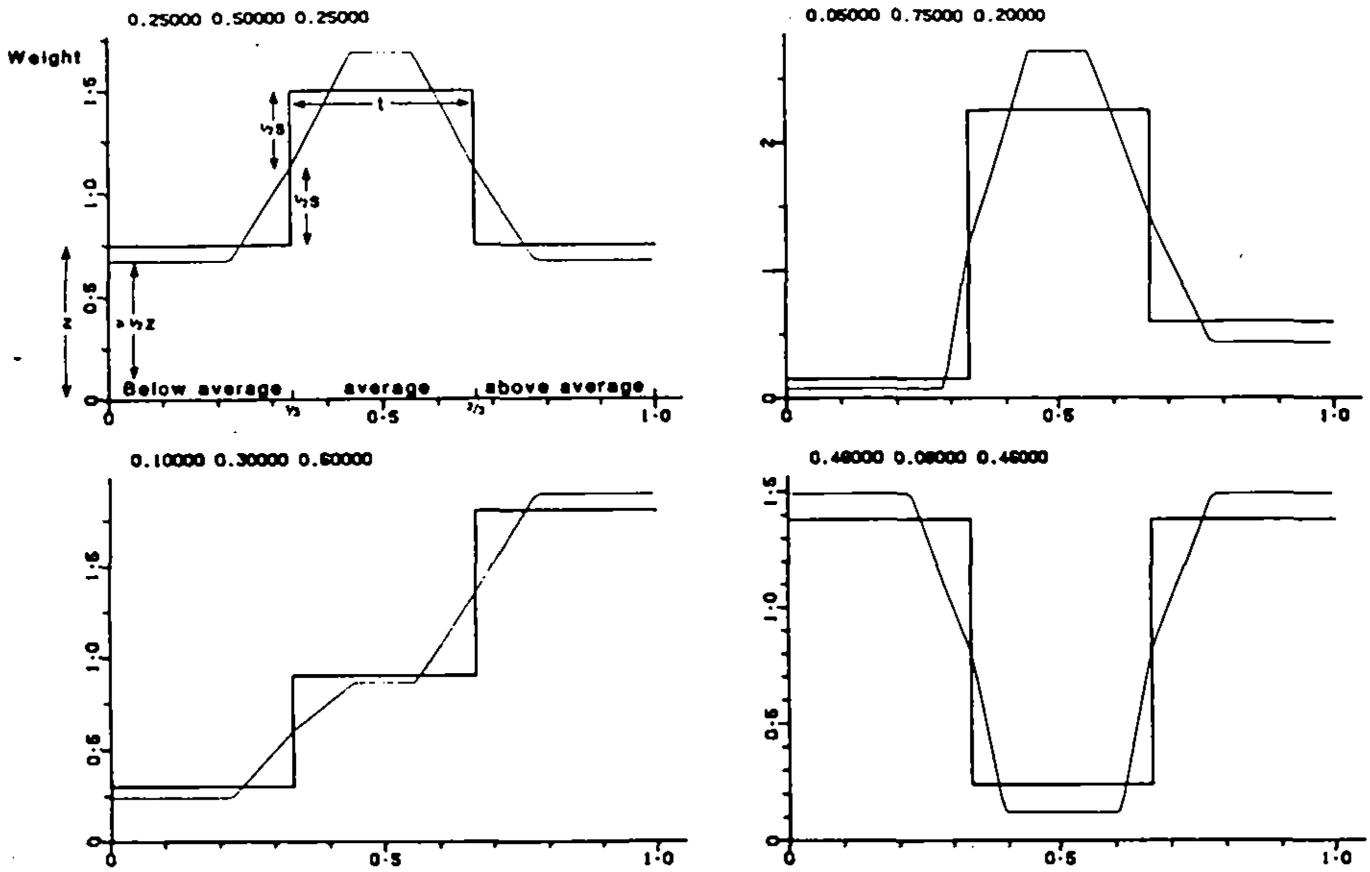


Figure 6 Piecewise linear smoothing function applied to a range of categorical probability rainfall forecasts

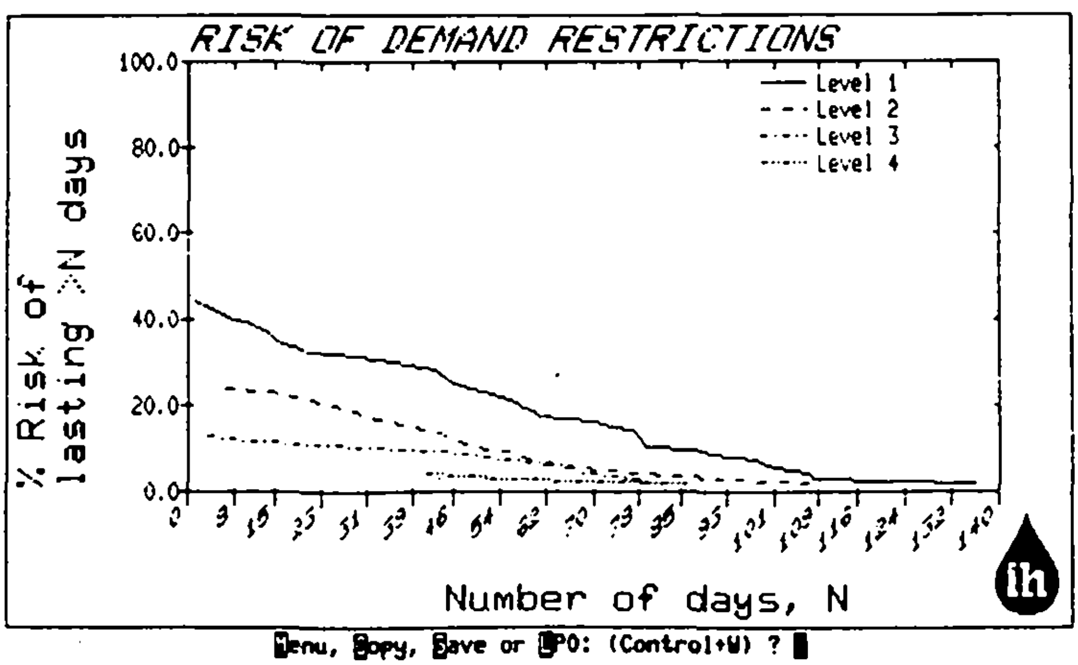


Figure 7 Risk of demand restrictions at different levels of severity lasting for more than a given number of days during the drought of 1976

the minimum and maximum storage levels obtained from the scenarios for each day of the forecast period.

Risk estimates are also made for the demand restrictions introduced as the total reservoir storage is depleted. These are presented graphically in terms of the risk of demand restrictions at different levels of severity lasting for more than a given number of days (Figure 7), and as a table displaying the risk of restrictions being at least as severe as indicated by each restriction level over the forecast period. Clearly the duration over which standpipes are to be used at a given level of risk is important as well as the risk that standpipes will be required at all. It would seem sensible to regard these risk estimates of demand restrictions as the most important source of information in tactical decision-making. Various average and extreme statistics are also calculated relating to pumping, supply deficits and storage levels.

CONFIDENCE LIMITS FOR RISK ESTIMATES

The specific level for which there is a given percentage risk of the reservoir storage falling below that level on a given day is essentially a quantile estimate associated with the probability distribution of reservoir storage for that day. The precision of this risk estimate is clearly of interest to the decision-maker. Since the quantile estimates have been determined through a plotting position formula, and not through fitting a parametric distribution to the storage values, what is required is a distribution-free confidence interval for quantiles. Such a non-parametric estimate is provided by the relation (David, 1981, p15)

$$Pr(S_{(\ell)} \leq s_p \leq S_{(u)}) = \sum_{i=\ell}^{u-1} \binom{n}{i} p^i (1-p^i)^{n-i} \geq 1-\alpha$$

Here, $S_{(\ell)}$ and $S_{(u)}$ are the ℓ'th and u'th ranked storage values out of n values obtained from the reservoir simulation model. They are the used to define the end points of a confidence interval such that the probability that this interval contains the population quantile, s_p, is at least $100(1-\alpha)\%$. For $p=0.5$, corresponding to the population median $s_p=s_{0.5}$, this simplifies to give the confidence interval $(S_{(\ell)}, S_{(n-\ell+1)})$, where ℓ is defined as the smallest value for which

$$0.5^n \sum_{i=\ell}^{n-\ell} \binom{n}{i} \geq 1-\alpha \ .$$

RAINFALL-RUNOFF MODELLING

In the Thames basin the effect of a dry summer on reservoir reliability is strongly influenced by aquifer recharge over the previous winter, and this is reflected in the component of flow attributed to groundwater. This phenomenon makes it crucial that a rainfall-runoff model accurately represents both the longer term component deriving from groundwater and the shorter term components deriving from recent rainfall. To this end a conceptual catchment model (Greenfield, 1984), developed specifically to represent the complex hydrological response of sub-basins of the Thames, was employed. The model structure comprises a Penman type soil moisture accounting procedure, with excess water subsequently passing downwards through linear and quadratic storages representing unsaturated and saturated storages respectively. This model structure is replicated for different hydrological response zones identified within a basin, different parameter values being used to obtain responses characteristic of aquifer, clay, riparian area, paved area, and sewage effluent zones. The sum of the responses from each zone gives the total basin hydrograph. Models were calibrated for the three sub-basins with outlets at the locations where statutory controls on abstraction amounts and residual flows are imposed. These models could then be used within the risk assessment procedure to transform rainfall scenarios into flow scenarios ready for use in the water resource system models.

INCORPORATION OF CURRENT HYDROLOGICAL CONDITIONS

On the day when a risk assessment of future reservoir conditions is to be made information will be available on the current hydrological condition of the basin. Information on daily natural flows will probably indicate that the rainfall-runoff model simulation is in error by a greater or lesser amount. This information may be used to adjust the internal state variables of the model, in the form of water storage contents, through an empirical state adjustment scheme. The scheme devised for use in the zonal conceptual model simply apportions the discrepancy between observed and simulated flow to each zone's flow in proportion to each zone's contribution to the total model flow. Specifically the empirical adjustment made to flow from the i'th zone, $Q^{(i)}$, takes the form

$$Q^{(i)*} = Q^{(i)} + \frac{Q^{(i)}}{Q}(Q^{o} - Q)$$

where Q is the total model flow and Q^{o} is the observed flow. (A further refinement is included to prevent flow from effluent or abstraction zones being adjusted.) This simple empirical state adjustment scheme has the property that the adjusted total model flow equals the observed natural flow on the day chosen for adjustment. Adjustments made on the recession limb serve to correct the model to give a potentially more accurate representation of drainage from groundwater, so critical to reservoir reliability. More formal state adjustment schemes based on the Kalman filter were avoided since these are only optimal for linear models and the approximate solutions that have been developed for nonlinear conceptual models offer no guarantee of being better than the simple empirical scheme presented here. An example of a state adjustment made on 1 May 1976 is indicated by an abrupt correction to the simulated flows on this date in Figure 8. An option to manually adjust a range of state variables within the model on a specified day provides considerable flexibility in the choice of adjustment, and could, for example, allow neutron probe measurements of soil moisture to be used as the basis for adjusting the soil moisture deficits developed in the Penman type stores.

DECISION SUPPORT SYSTEM FOR DROUGHT MANAGEMENT

The overall risk assessment procedure described above and summarised in Figure 4 is implemented on a PDP11/73 microcomputer as an interactive menu-and-form driven decision support system (Moore et al., 1986b). Heavy reliance is placed on colour graphical displays to present the results to the user in an easily assimilated form. The control menu presenting the main analyses available to the user is illustrated in Figure 9. A powerful data handling system allows changes to be made to the operating policy through a series of menus and forms; the modified operating policies thus created may be given identification names and stored for subsequent use in the water resources system model. A key feature of the system, which allows daily rainfall-runoff simulations and state adjustments to be made right up to 0900 hr on the current day, is an automatically updated archive of hydrometric data. This archive is maintained through a real-time communication link with a second computer dedicated to real-time data acquisition via telemetry.

Real-time risk assessments of water supply for forecast periods starting on the current day and extending up to one year ahead can be made with great ease. If the assessment indicates a potential supply shortfall, it is an easy matter to modify the long-term operating strategy, for example by relaxing statutory constraints or assuming that some of the demand is catered for by another source, and to observe the resulting change in system reliability. Thus the system serves as a valuable support tool for tactical decision- making during drought management. The decision support system is now used operationally by Thames Water's Regulation and Monitoring Division.

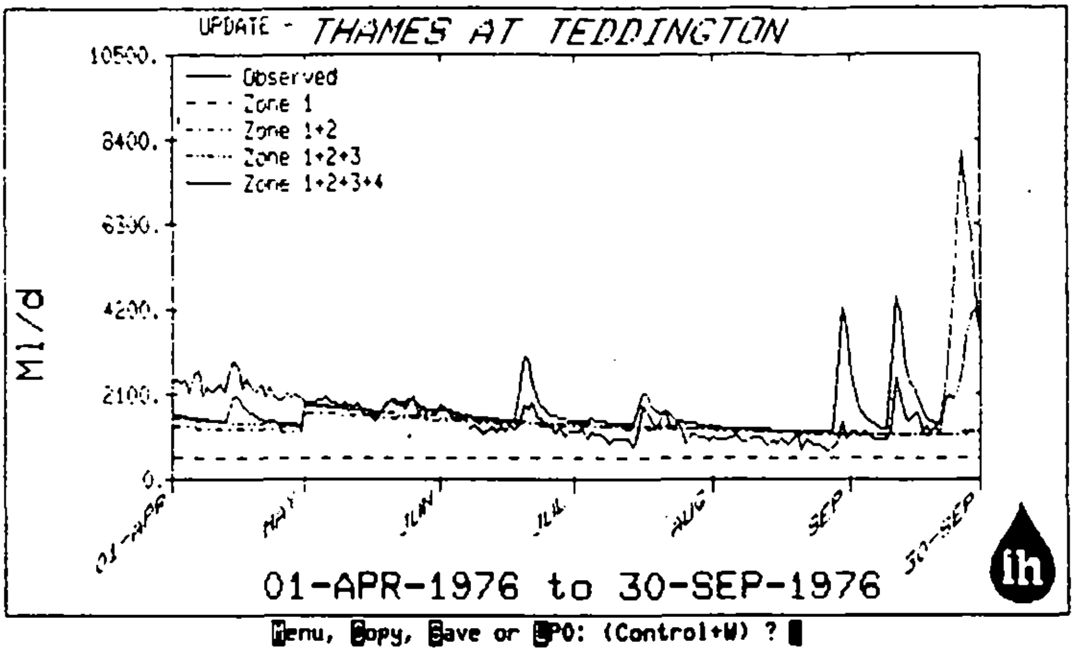


Figure 8 Empirical state adjustment applied to the zonal components of flow from the rainfall-runoff model on 1 May 1976

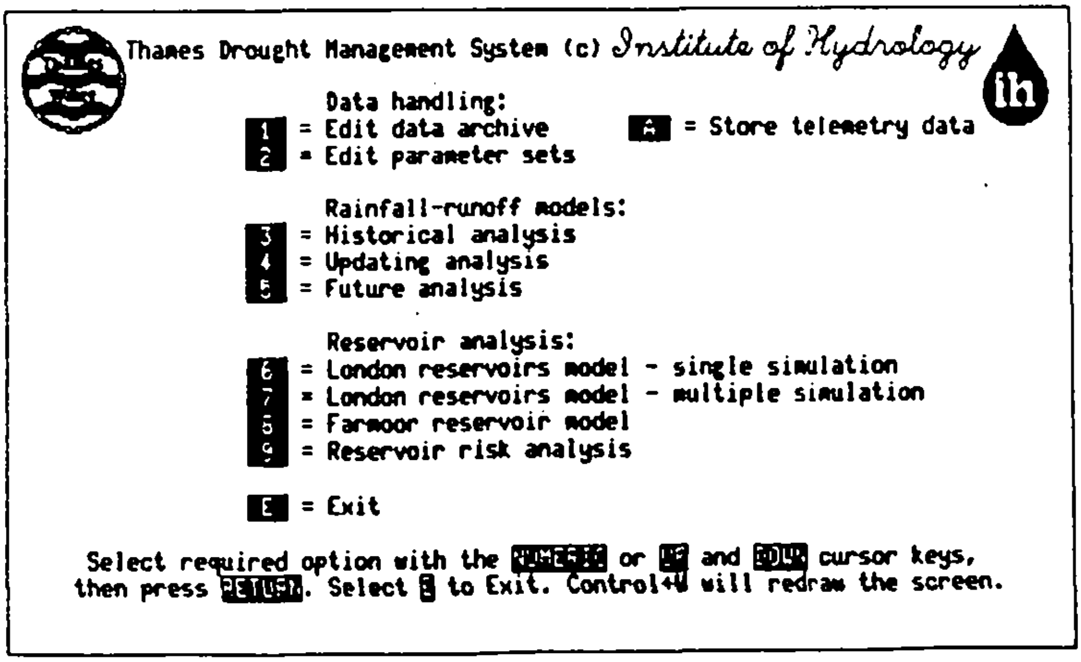


Figure 9 The control menu of the decision support system for drought management

ACKNOWLEDGEMENTS

The work described was initiated and financially supported by Thames Water. Particular thanks are due to Mr A.E. Jones of Thames Water for giving support and encouragement at all stages of the project. Assistance provided by Thames Water and Institute of Hydrology staff during the project is also gratefully acknowledged.

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ANNEX V

NERC CONDITIONS OF AGREEMENT

NATURAL ENVIRONMENT RESEARCH COUNCIL

TITLE . . . .

. . . .

THIS AGREEMENT IS MADE BETWEEN THE NATURAL ENVIRONMENT RESEARCH COUNCIL (HEREINAFTER REFERRED TO AS "THE COUNCIL") ON THE ONE PART AND . . . . (HEREINAFTER REFERRED TO AS "THE CUSTOMER") ON THE OTHER PART FOR THE CARRYING OUT BY THE COUNCIL OF THE PROGRAMME OF WORK (HEREINAFTER REFERRED TO AS "THE WORK") SET OUT IN SCHEDULE 1.

IT IS HEREBY AGREED THAT THE FOLLOWING TERMS AND CONDITIONS AND THE GENERAL CONDITIONS OVERLEAF, SHALL APPLY TO THE ABOVE AGREEMENT.

1. Programme of Work
The Work as detailed in Schedule 1 will be undertaken in . . . . by the . . . . (hereinafter referred to as "the . . . .) a component Institute of the Council.

2. Duration
The Work shall begin on . . . . and shall be completed by . . . . subject to extensions by agreement between the Customer and the Council (see General Condition 18).

3. Fees and Expenses

4. Payment
Payment of the sum/sums set out in Condition 3 shall be made . . . .

Cheques made payable to the Natural Environment Research Council should be sent to:–

Accounts Section . . . .

. . . .

All payments apart from any due prior to commencement of the Work, will be made within 30 days of receipt of invoice. If payments are not made by the due date then the Council may claim interest at a rate of 2 per cent per month thereon for the period from the due date to the date on which payment is eventually made.

5. Nominated Officers
The Nominated Officers who will provide for liaison between the Customer and the Institute on all aspects of the Work shall be:–

For the Institute . . . .

Address . . . .

. . . .

Telephone . . . . Telex . . . .

For the Customer . . . .

Address . . . .

. . . .

Telephone . . . . Telex . . . .

FOR AND ON BEHALF OF

Date . . . . 19 . . . .

FOR AND ON BEHALF OF THE NATURAL ENVIRONMENT RESEARCH COUNCIL, POLARIS HOUSE, NORTH STAR AVENUE, SWINDON SN2 1EU

Date . . . . 19 . . . .

C1/3 (Revised September 1984)

GENERAL CONDITIONS

1. **Obligations of the Customer**

Insofar as it is within its control, the Customer shall take all steps necessary to enable the Council to perform its obligations and exercise its rights under the Agreement without interruption or hindrance. The obligations of the Customer shall include but not be restricted to:–

(a) Preparation and provision of facilities, if applicable, answering all enquiries by the Council and all requests for access to and provision of relevant reports, papers, data, maps, etc in such a way as to facilitate the services of the Council hereunder.

(b) Ensuring that without cost to the Council and its Institute Personnel that the Council and its Institute Personnel have the necessary powers, rights, authorities, consents, approvals, visas, work permits and residence permits to enable the Council and its Institute Personnel to commence, carry out and complete the Work.

(c) Ensuring that Institute Personnel engaged on the Work are at all times permitted to enter, work in, or leave the country in which work is to be carried out as required.

(d) Ensuring that the equipment, materials, tools and supplies required for the Work in the country in which the work is to be carried out can be expeditiously imported and exported without payment of any duties or taxes.

(e) Ensuring that Institute Personnel engaged on the Work are at all times permitted to enter and leave the area in which the Work is to be performed in the country in which the work is to be carried out without interruption or hindrance.

(f) Ensuring that the Council and its Institute Personnel engaged in the Work in the country in which the work is to be carried out shall be exempt from all present and future taxes, and charges of a like nature, levies and duties, provided that if such exemption is not obtained then such present and future taxes, charges, levies and duties shall form an addition to the costs as defined in Condition 3 and shall be paid by the Customer accordingly.

(g) In the event of the Customer failing to meet any of its responsibilities under this General Condition 1 the Council shall, without prejudice to any other rights or remedies to which it is entitled under the Agreement, be entitled to suspend the Work or any part thereof for such period or periods and in such manner as the Council may deem to be necessary. Any additional cost arising from such suspension shall be borne by the Customer.

2. **Changes in Law and Regulations in affecting the Work**

In the event of any change in the law or regulations of the country in which the work is to be carried out or in the interpretation of such laws or regulations or in the exercise of any administrative discretion by any relevant governmental authority occurring after the commencement of this Agreement and where such changes significantly affect the Work, the parties will negotiate with the view to reaching agreement on variations to this Agreement which will compensate the Council for the consequences of any such changes. If the parties fail to reach agreement the Council may terminate the Agreement with immediate effect by notice in writing.

3. **Obligations of the Council**

(a) The Council will provide suitably qualified Personnel to carry out the Work and will use all due skill and care so as to carry out the Work in accordance with accepted professional standards and ensuring the accuracy and quality of the Work.

(b) This Agreement shall not otherwise contain any condition or warranty express or implied as to the quality, accuracy or suitability for any use of the Work or the results thereof and no such condition or warranty is to be taken to have been given or implied from anything said or written in any negotiations or discussions between the parties or their servants or agents.

(c) The Council shall not be liable for any loss or damage including consequential loss or injury or death resulting from or arising out of any use of the Work or the results thereof or anything done or omitted to be done in reliance on the Work or the results thereof by the Customer or by any third party except insofar as the same is attributable to the negligence or to a lack of due skill and care on the part of the Council.

4. **Management of the Work**

(a) The management of the Work shall be the responsibility of the Council who in particular shall be responsible for:–

(i) The determination of how the Work is to be carried out, including where and by whom the Work is to be done and whether the arrangements are to be by direct employment, sub-contract or other arrangements;

(ii) The management of all Institute Personnel and local employees, including the sole right to issue instructions to such Personnel and local employees and sub-contractors as may be legitimate under the terms of the sub-contract.

(iii) The Council will discuss the arrangements in General Condition 4(a) (i) with the Customer and give due consideration to proposals or representations from the Customer concerning them.

5. **Replacement of Personnel**

(a) The Council shall have discretion as to the attendance and withdrawal of the services of specific Institute Personnel from time to time which discretion shall be used in the best interests of the completion of the Work.

(b) If the Customer requests replacement due to inadequate performance by Institute Personnel which is proved by the Customer to be lower than the accepted professional standards or some other reason attributable to the proven negligence or misconduct of the Institute Personnel then the Customer may on giving reasonable notice to the Council request the replacement of the personnel at cost of the Council.

(c) If the Customer requests the replacement other than under General Condition 5(b) of the services of particular Institute Personnel then the Customer shall pay the costs thereof including the cost of return to the United Kingdom, an additional 3 months salary plus associated costs in respect of the particular Institute Personnel concerned and the cost of providing a replacement.

6. **Reports**

The Council shall provide the Customer with progress reports in such form at such intervals and as agreed between the parties. Scientific/Technical Reports of the various aspects or stages of the Work shall be completed as soon as practicable and complete final report or reports at the termination of the Work.

7. **Termination**

(a) Either party may (without prejudice to any other remedy available to it in respect of the breach) terminate this Agreement forthwith by notice to the other if the latter fails to observe or perform any of its obligations under this Agreement and has been notified in writing by the party aggrieved of the nature of the failure and omits to remedy such failure within such reasonable period as shall be specified in such notice.

(b) Should the Agreement be terminated under General Condition 12 or for any reason by the Customer or by reason of default by the Customer then the Council shall be paid by the Customer (insofar as such amounts or items shall not already have been covered by payments on account made to the Council) for all Work executed prior to the date of termination plus any costs, expenses and allowances then outstanding and any other costs or expenses incurred by the Council as a consequence of such termination including but not restricted to:–

(i) The cost of any materials or goods reasonably ordered by the Council which shall have been delivered to the Council or in respect of which the Council is legally liable to accept delivery provided that such materials and goods are required by the Council to carry out the Work.

(ii) A sum being the amount of expenditure reasonably incurred by the Council in the expectation of completing the whole of the Work insofar as such expenditure shall not have been covered by the payments to be made pursuant to General Condition 7(b).

8. **Indemnity Provided by the Customer**

(a) The Customer shall indemnify the Council against all actions and liabilities of whatever nature or description (including expenses incurred in connection therewith) in any way arising out of:–

(i) any act or omission of the Council in the performance or purported performance of this Agreement except insofar as such act or omission arises out of negligence on the part of the Council or from any failure by the Council to use due skill and care.

(ii) any use of, or anything done or omitted to be done in reliance upon the Work or the results thereof by any third party except insofar as such action claim or liability arises out of negligence on the part of the Council or from any failure by the Council to use due skill and care.

(b) The Customer shall not make any claim or bring any action or proceeding against the Council in respect of any expenses incurred by or any loss of or damage to any property or injury or death to any person or consequential losses sustained by the

Customer as a result of any act or omission of the Council whilst engaged in the performance or purported performance of this Agreement except insofar as the same is attributable to the negligence or to a lack of due skill and care on the part of Council.

(c) The liability of the Council howsoever arising in respect of or attributable to any breach, non observance or non performance of the Agreement or any error or omission shall be limited to the total fees due to the Council.

9. Exploitation of Council Expertise

Nothing in this Agreement shall prevent the Council from carrying out any Work, or providing advice or information on any subject including the type of Work described in the Schedule, to any other person or organisation nor prevent the Council from exploiting its expertise as it sees fit provided the execution of this Agreement is not affected by the carrying out of such Work.

10. Law (English)

The Agreement shall be considered as an Agreement made in England and subject to English Law.

11. Arbitration (English Law)

All disputes, differences or questions between the parties to the Agreement with respect to any matter or thing arising out of or relating to the Agreement, other than a matter or thing as to which the decision of the Council is under the Agreement to be final and conclusive and except to the extent to which special provision for arbitration is made elsewhere in the Agreement, shall be referred to the arbitration of two persons, (one to be appointed by the Council and one by the Customer or their Umpire), in accordance with the provisions of the Arbitration Act, 1950 and the Arbitration Act 1979 or any statutory modification or re-enactment thereof. Before resorting to arbitration both parties shall use their best endeavours to settle any disputes, differences or questions referred to above.

12. Force Majeure

(a) Neither party in this Agreement shall be liable for damage nor have the right to terminate this Agreement except as stated hereinafter by reason of any delay or default by either party in performing its obligations hereunder if such delay or default is caused by Force Majeure which without prejudice to the generality of the foregoing shall include acts of government, civil commotion and riot, hostilities, war, whether declared or not, fire, storm, tempest, strikes, lockouts, industrial disputes, delays by other contractors, or any other cause beyond the control of the Parties which could not have been foreseen at the date of signature of this Agreement.

(b) In the event of any of the circumstances specified in General Condition 12(a) resulting in any extra costs and/or any addition to the Work the Customer shall pay the Council for such extra costs and/or such additional duties. As soon as possible after the occurrence of the circumstances specified in General Condition 12(a), the party claiming Force Majeure shall give notice and full particulars in writing to the other party of such Force Majeure if the first party is thereby rendered unable wholly or in part to perform its duties under this Agreement.

(c) In the event that either party is prevented, hindered or delayed in the carrying out of the Work or any of its contractual obligations by reason of any of the causes referred to in General Condition 12(a) above then the parties shall immediately consult together to decide what course of action should be adopted. If the parties hereto have not been able to reach an agreement upon the course of action or upon any necessary modifications to the terms of the Agreement then either party shall thereupon be entitled to terminate the Work whereupon the provisions of General Condition 7(b) shall apply.

13. Copyright, Confidentiality and Publication

(a) *Copyright*

(i) The copyright of the maps, reports and all data arising out of the Work under this Agreement shall be vested in the Customer.

(ii) The copyright in maps, reports and all data supplied by the Council for the purposes of the Agreement other than those for which copyright is vested in the Customer under (i) above is and will remain vested in the Council.

(iii) The copyright in all maps, reports and data furnished by the Customer for the purposes of the Agreement is and will remain vested in (and remain the property of) the Customer.

(b) *Confidentiality*

(i) The Council shall exercise proper commercial prudence in preserving the confidentiality of information arising out of the Work under this Agreement.

(ii) Any information exchanged between the parties under (a)(ii) and (a)(iii) above will be safeguarded and, unless agreed otherwise, treated as, confidential by the recipient and not disclosed to third parties except in connection with the performance of this Agreement. This obligation shall continue in force notwithstanding the expiry of the term of this Agreement unless the parties agree otherwise or such information becomes public knowledge otherwise than in breach of this Condition.

(c) *Publication*

Subject to the approval of the Customer, which shall not be unreasonably withheld, the Council shall be allowed to publish scientific papers based on the Work, and no fee shall be payable thereon by the Council.

14. Council/Customer Equipment

(a) Equipment supplied by the Customer for the Work shall remain at all times the property of the Customer and shall be returned by the Council in accordance with procedures to be determined by the Customer and agreed with the Council.

(b) Equipment purchased by the Customer or by the Council for the Customer for the purposes of the Work shall be the property of the Customer.

(c) Equipment and tools purchased with Council funds and used for the Work shall remain the property of the Council.

15. Independent Contractor

Nothing contained herein shall be construed as establishing or creating between the Customer and the Council the relationship of master and servant or principal and agent, it being understood that the position of the Council in performing the Work is that of an independent contractor.

16. Assignment

This Agreement is personal to the parties and neither party may without consent of the other party assign their rights or obligations.

17. Amendment to Agreement

This Agreement contains the entire understanding of both parties and may only be varied in writing signed by their authorised representatives.

18. Variations to the Work

(a) The Customer may, at any time, request the Council to make variations to the Work under this Agreement provided that the Council shall not be obliged to effect such variations until agreement in writing has been reached between the parties.

(b) Before any such variation can be agreed an estimate of the cost of such variation shall be notified to the Customer in writing.

(c) In the event of the parties hereto agreeing any variation to the Work in the manner agreed above then the price of the Agreement shall be amended accordingly.

19. Notices

(a) Any notice or request by either party to the Agreement shall be given by sending the same by prepaid post, cable, telegram or telex to the address of the other party to the Agreement.

(b) Unless otherwise agreed in writing all communications and documents exchanged between the parties in the performance of any obligations under this Agreement shall be in the English language.

Natural
Environment
Research
Council

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The Institute of Hydrology is a component establishment of the Natural Environment Research Council