Interim Report R&D Project 298/1/T

Evaluation of Frontiers and Local Radar Rainfall Forecasts for use in Flood Forecasting Models

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EXECUTIVE SUMMARY

Previous weather radar studies undertaken by the Institute of Hydrology have focussed on the understanding and improvement of weather radar in measuring and forecasting rainfall fields for flood warning purposes. These studies have resulted in operational systems for real-time raingauge calibration of weather radar and for rainfall forecasting over the Thames basin. The present study represents a natural extension of this work through an assessment of the influence of using different forms of rainfall as input to flood forecasting models. The forms of rainfall input considered derive either from raingauges or weather radar data in its raw form, in raingauge calibrated form and in the form of forecasts derived from the national Frontiers and Local Radar Rainfall Forecasting systems. Whilst the major thrust of the Study is the assessment of the Frontiers and local radar rainfall forecasts for use in rainfall-runoff models for real-time flood forecasting, a secondary objective is an assessment of different model types. This will be achieved through the use in the evaluation of four types of model and eight study catchments, with varying hydrological characteristics.

This interim report on the two year study describes progress in establishing a database for the eight study catchments and reviews the four models to be employed. Three of the four models have been developed and integrated into the Institute of Hydrology's model calibration and assessment environment. Most significantly an infrastructure has been created and proven which incorporates the different types of observed and forecast rainfall inputs into this modelling environment, allowing a variety of forms of assessment to be made. The operation of part of this infrastructure is demonstrated using rainfall input from weather radar in observed and forecast form from the two radar rainfall forecasting systems under test. A single flood event, model type and catchment are used for the purposes of illustration. Finally, a strategy for assessment of the variety of options under test is developed drawing on factorial experimental design concepts.

ACKNOWLEDGEMENTS

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CONTENTS

1. INTRODUCTION

This report summarises the progress made in the first year of a project which aims to assess the value of radar-derived rainfall forecasts in flood forecasting models used for operational flood warning. It also describes the theoretical background to the models, develops a strategy for assessment and provides a partial illustration of its application.

The main area of work in the initial stage of the project was the establishment of a database to provide the foundation for the evaluation study. This work is reported in Section 2.

Four flood forecasting models: the Thames Conceptual Model (TCM), the Isolated Event Model (IEM), the Probability Distributed Model (PDM), and (to a limited extent) the Synthetic Unit Hydrograph Model (SUHM), are to be used for the assessment. The theoretical background to these models is presented in Section 3. Incorporation of the TCM and IEM into the calibration and assessment software originally developed for the PDM has been the second major area of work, and is described in Section 4, along with progress on the other models.

Radar-derived rainfall forecasts for the Thames region are available from the IH Local Radar Forecast System and the Met. Office Frontiers system. These two types of forecast are described briefly in Section 5. The most recent development work has been to create a mechanism for incorporating these rainfall forecasts within the flow forecasting scheme used by the rainfall-runoff models.

The skeleton of the full evaluation procedure is now in place, and Section 6 provides a preliminary discussion of the methodology of this procedure. This concludes with an illustration of the evaluation of different rainfall forecasts and operating modes using one type of model applied to a single event and catchment.

Finally, Section 7 gives a summary of the progress made to date together with plans for future work.

2. DATABASE FOR ASSESSMENT

2.1 Introduction

In order to ensure that the results of the assessment are representative across a range of hydrological environments, a set of eight catchments have been selected spanning a range of areas, lithologies and land use. However, the study catchments have been restricted to the Thames basin because of the availability of both Local Radar Rainfall Forecast and Frontiers data for this region. The characteristic features of the 8 catchments are summarised in Table 2.1.1.

Table 2.1.1 The study catchments and their main characteristics

Catchment	Characteristic
Silk Stream at Collindeep Lane	small, urban
Beverley Brook at Wimbledon Common	small, mixed urban/rural
Roding at Redbridge	medium, rural
Wey at Weybridge	large, mixed urban/rural
Mole at Kinnersley Manor	medium, clay
Colne at Denham	large, mainly chalk
Pinn at Uxbridge	small, urban
Cobbins Brook at Sewardstone Road	small, mixed urban/rural, clay

The main source of data used in the Study are 15 minute values of flow and rainfall, both gauged and radar-derived. These data were derived from two main NRA archives, the Ferranti-Argus archive at Reading and the VAX archive at Waltham Cross. The following sub-sections outline the progress made in establishing and verifying flow, raingauge rainfall, radar rainfall and evaporation data for use in the evaluation of the flood forecasting methods. Work has focused particularly on correction and quality control of data from the Ferranti-Argus archive, and the generation of catchment-average rainfalls from radar data.

The observational data are held at IH on a VAX/RdB relational database. Forecast data, because of their synthetic and relatively ephemeral nature, are held in individual files relating to specific catchments, events, and forecast types. Rainfall forecasts are discussed in Section 5.

2.2 Flow Data

Ferranti-Argus data archive

The four stations for which flow data are available on the Ferranti-Argus archive are listed in Table 2.2.1 below. Periods of record presently transferred to the IH archive are indicated along with each station's grid reference and catchment area.

Table 2.2.1 Flow data from the Ferranti-Argus data archive

Station number	Station name	Grid reference	Area km^2	Period of record
39098	Pinn at Uxbridge	5062 1826	33.3	1, 2, 10, 11/1990
39069	Mole at Kinnersley Manor	5262 1462	142	1, 2, 10, 11, 12/1990, 1/1991
39010	Colne at Denham	5052 1864	743	10/1987 2,3, 12/1989 2/1990
39079	Wey at Weybridge	5068 1648	1008	2, 3, 12/1989 1, 2/1990 1/1991

Zero values are common in the data for Kinnersley Manor and Weybridge, and have been flagged as missing in putting them on the IH modelling database. Records for Weybridge are rather erratic. Mean and peak daily flows calculated from the 15-minute data for Kinnersley Manor, Weybridge and Uxbridge have been cross-checked against tabulated mean and peak daily flows provided by the NRA; the latter were calculated from hourly values on the NRA's 'local archive'. Inspection of the plots supplied with the tables suggests that the only significant discrepancies are due to errors in the hourly data.

VAX data archive

The IH modelling database currently holds 15-minute level data for October, November and December 1990 for the four stations listed below.

Table 2.2.2 Flow data from the VAX data archive

Station number	Station name	Grid Reference	Area km^2
039049	Silk Stream at Collindeep Lane	5217 1895	29.0
038020	Cobbins Brook at Sewardstone Road	5387 1999	38.4
039005	Beverley Brook at Wimbledon Common	5216 1717	43.6
037001	Roding at Redbridge	5415 1884	303.3

2.3 Raingauge Rainfall Data

15-minute data from the Ferranti-Argus data archive

Raingauge data held on the Ferranti-Argus archive are listed below along with the periods of record transferred to the IH database.

Raingauge data files were supplied in RAINARK and ICL formats. The former contain start/stop indicators which are not always used consistently, and some care is required to ensure that the procedure used to generate time-series of 15-minute rainfall does not create erroneous missing values. The following interpretation rules are used:

i) the "data missing" flag is initially set;

ii) a rainfall value of -1.0 toggles between "data missing" and "data present";

iii) a non-negative rainfall value forces "data present";

iv) 15-minute slots falling entirely within a "data missing" period are assigned missing values;

v) 15-minute slots containing a toggle to "data missing" are assigned missing values only if they contain no rainfall and the previous slot is also missing (this prevents the common combination of "0900 off, 0905 on" from generating a missing slot).

Daily rainfall totals from the 15-minute data were cross-checked against the tabulated values (from hourly data) supplied by the NRA Thames Region. Not all the periods covered by the 15-minute data were summarised in these tables, and two tables (Radlett and Chenies for February 1990) contained obviously duplicated data. Problems identified by this and other quality checks are listed in Table 2.3.2. Most of these have either been resolved or accommodated since the table was first drawn up.

Table 2.3.1 Raingauge data from the Ferranti-Argus data archive

Raingauge	Station no	Grid reference	Altitude m AOD	Period of record
Bordon Camp S. Wks	281185	4803 1361	74	2, 3, 4, 12/1989
Burstow S. Wks	284702	5305 1437	58	1, 2, 10, 11, 12/1990 1/1991
Camberley S. Wks	271490	4862 1598	60	2, 3, 4, 12/1989 1, 2/1990, 1/1991
Chenies	278744	5017 1999	138	10, 11/1987 2, 3, 4, 12/1989, 2/1990
Cranleigh S. Wks	282289	5041 1392	47	2, 3, 4, 12/1989 1, 2/1990 1/1991
Guildford, Woking Rd S. Wks	282777	5000 1515	30	1/1991
Leatherhead S. Wks	285629	5160 1556	55	2, 3, 4/1989 1, 2, 12/1990 1/1991
Radlett, Blackbird's S. Wks	277406	5148 2002	79	10, 11/1987 2, 3, 4, 12/1989 1, 2, 10, 11/1990

15-minute data from the VAX data archive

The IH modelling database currently holds 15-minute rainfall data from October, November, December 1990 and January 1991 for the stations presented in Table 2.3.3, with the exception of Stanford Rivers (238943) and Wanstead (239397) which were not available for these months because these are new stations.

Table 2.3.2 Problems with Ferranti-Argus rainfall data 1991

Station	Date	Problem
Colne at Denham rainfall stations		
Radlett	6 Oct 1987	15 minute total = 0.0mm, hourly total = 6.2 mm.
Chenies	29 Oct 1987	Bad value (72.8mm) at 1115. Not part of an event.
Radlett	24 Dec 1989 to 28 Dec 1989	Missing from end of RADDEC89.
Chenies	as above	Missing from end of CHEDEC89.
Chenies	1 Feb 1990 to 3 Feb 1990	Accumulation sets to 0.0 minutes in CHEFEB90.
Mole at Kinnersley Manor rainfall stations		
Burstow	Feb 1990	Note in header of file BURFEB90 states "rainfall suspect gauge under recorded".
Burstow	13 Feb 1990 to 15 Feb 1990	Flagged missing in BURFEB90, but present in hourly data
Burstow	26 Oct 1990	15 minute total = 15.6mm, hourly total = 8.6mm due to 6.6mm extra rain between 1040 and 1230.
Burstow	31 Dec 1990	Missing from end of BURDEC90.
Burstow	8 Jan 1991	15 minute total = 7.8mm, hourly total = 23.0mm.
Wey at Weybridge rainfall stations		
Camberley	22 Feb 1989	15 minute total = 3.8mm, hourly total = 1.6mm.
Camberley	23 Dec 1989	15 minute total = 4.0mm, hourly total = 6.4mm.
Leatherhead	20 Dec 1989 to 28 Dec 1989	Data file LEADEC89 missing. (LEADEC90 was supplied instead)
Cranleigh	23 Dec 1989	15 minute total = 5.2mm, hourly total = 8.8mm.
Camberley	3 Jan 1991	15 minute total = 4.6mm, hourly total = 2.0mm.
Pinn at Uxbridge rainfall stations		
Radlett	13 Feb 1990 to 15 Feb 1990	Flagged missing in RADFEB90, but present in hourly data

Table 2.3.3 Raingauge data from the VAX data archive.

Station name	Site id	Hydrometric Number	National Grid Reference
Moreton	166	166166	5533 2068
Thornwood	107	238604	5476 2048
Stanford Rivers	175	238943	5545 2002
Epping	167	239528	5412 1981
Chigwell	108	239315	5423 1926
Wanstead	176	239397	5415 1882
Harrow Weald	14	246860	5153 1920
Mill Hill	15	246627	5231 1917
Putney Heath	7	287283	5234 1737
Hogsmill	10	286392	5194 1682
Cheam	65	287141	5247 1641
How Green	9	287451	5283 1581

Daily rainfall data

Daily rainfall for the three years 1988, 1989 and 1990 for the raingauges listed below has been entered into the modelling database.

281185 Bordon
284702 Burstow
271490 Camberley
287141 Cheam
282289 Cranleigh
282777 Guildford
286392 Hogsmill
287451 How Green
285629 Leatherhead
277406 Radlett
238604 Thornwood

Daily rainfall for most of 1991 are also available at these stations, with the exception of Cheam, Hogsmill, How Green, and Thornwood, and the addition of Chenies (278744) and Farnham (280825).

These data are required in the study to perform continuous soil moisture accounting at a daily time interval between identified storm events.

2.4 Radar Rainfall Data

Catchment-average rainfall totals at 15 minute time intervals for all 8 flow stations have been derived from 2km gridded radar data for January and February 1990, the last three months of 1990, and January 1991. The radar data used are uncalibrated values which have been preprocessed to correct for anomalies in the radar field (see the Final Report on the London Weather Radar Local Rainfall Forecasting Study). Calculation of the catchment averages employs a digitised catchment boundary and a raster scanning algorithm to identify the proportion of each 2 km grid square within the catchment: the proportions are then used as weights to calculate the average catchment rainfall from the radar grid square values.

2.5 Potential Evaporation Data

For the purpose of comparison between the Thames and IH implementations of the Thames Conceptual model, the procedure used in the Thames program FLUD2 for calculating potential evaporation from a fixed set of monthly values has been coded as a pseudo-database access. That is, a request for PE values from the station "Thames Fixed" causes the access routine to generate appropriate values internally.

In addition, potential evaporation data supplied by the NRA has been entered on the modelling database. It comprises daily values for a 'standard' year, and monthly totals for particular regions and years.

The evaporation regions are:

Thames Standard
Lower Wey
North Downs - Hampshire (P)
Wey - Greensand (S)
Upper Mole
Chilterns - East - Colne (N)
Lower Lee

and totals are held for the months October 1986 to June 1991 inclusive. The pseudo-region "Thames Standard" holds the monthly totals for a standard year, and the mean monthly totals for each station are associated with year 0.

The database access routine first generates monthly totals for a requested station and range of dates, using observed values where available, and long-term means if not available. Daily values may then be generated by one of two methods:

i) apportionment of each monthly total in the same daily proportions as in the corresponding month of the 'standard' year, or

ii) linear interpolation between the 16th days of successive months.

The methods are not significantly different for the standard year, whilst the former gives discontinuities between months for monthly totals other than standard. For this reason, the interpolation method will be used in this study. Figure 2.5.1 shows the daily evaporation profile for the standard year and for 1988 for the Upper Mole using this method. The facility to obtain a weighted average of values from more than one station will be provided at a later date.

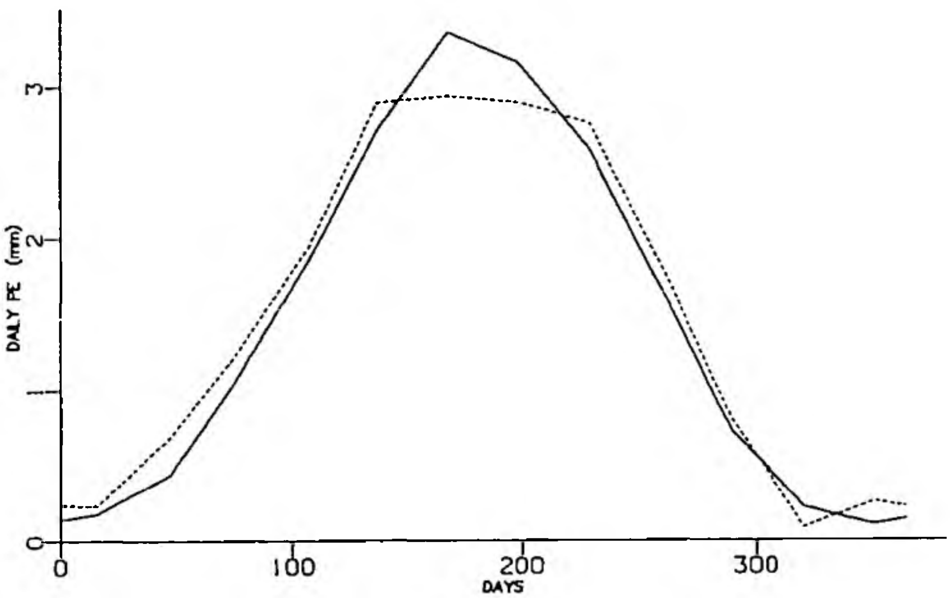


Figure 2.5.1 Daily potential evaporation profile in mm for the standard year (solid line) and for 1988 (dashed line) for the Upper Mole

3. FLOOD FORECASTING MODEL THEORY

3.1 Introduction

Four conceptual models of the rainfall-runoff process are to be used in the evaluation. Three of these - the Thames Conceptual Model (TCM), the Isolated Event Model (IEM) and the Probability Distributed Model (PDM) - are based on the combination of a soil moisture store (used indirectly by the IEM) with one or more linear or non-linear reservoirs and a pure time delay. The IEM is the simplest of the three and the TCM, which allows multiple zones, is the most complex. The PDM is rather more sophisticated than any one zone of the TCM, whilst requiring only a modest number of parameters. The fourth model, the Synthetic Unit Hydrograph Model (SUHM), has a more spatially-distributed formulation than the other models and requires ancilliary information, such as survey data, to support its configuration to a given catchment. As such, it is less amenable to automatic calibration, and will only be applied to two urban catchments to which it has already been configured.

Purely statistical models relating flow to rainfall are not considered, although all the conceptual models have the facility to employ an ARMA time-series model to predict the errors between observed and simulated flow.

3.2 The Thames Conceptual Model

The structure of the Thames Conceptual Model, or TCM, is based on subdivision of a basin into different response zones representing, for example, runoff from aquifer, clay, riparian and paved areas and sewage effluent sources. Within a given zone the same vertical conceptualisation of water movement is used, the different characteristic responses from the zonal areas being achieved through an appropriate choice of parameter set, some negating the effect of a particular component used in the vertical conceptualisation.

Specifically, within a given zone water movement in the soil is controlled by the classical Penman storage configuration (Penman,1949) in which a near-surface storage, of depth equal to the rooting depth of the associated vegetation (the root constant depth), drains only when full into a lower storage of notional infinite depth (Figure 3.2.1). Evaporation occurs at the Penman potential rate, E, whilst the upper store contains water and at a lower rate, E_a, when only water from the lower store is available (Figure 3.2.2). The Penman stores are replenished by rainfall, but a fraction ϕ (typically 0.15) is bypassed to contribute directly as percolation to a lower "unsaturated storage". Percolation occurs from the Penman stores only when the total soil moisture deficit has been made up. The total percolation forms the input to the unsaturated storage which behaves as a linear reservoir, with the outflow rate q being related to its store of water s through the relation $q = s/k$, where k is the time constant of the reservoir. This outflow, or more correctly the integrated volume over an interval, acts as an input called "recharge" to a further storage representing storage of water below the phreatic surface in an aquifer. Withdrawals are allowed from this storage to allow pumped groundwater abstractions to be represented. A quadratic storage representation is used here where the outflow rate, Q, is related to the storage of water, S, through the relation $Q = S^2/K$ where K is a nonlinear storage constant. The actual algebraic expressions in each of these two storages are presented later in this section and a review of the theoretical

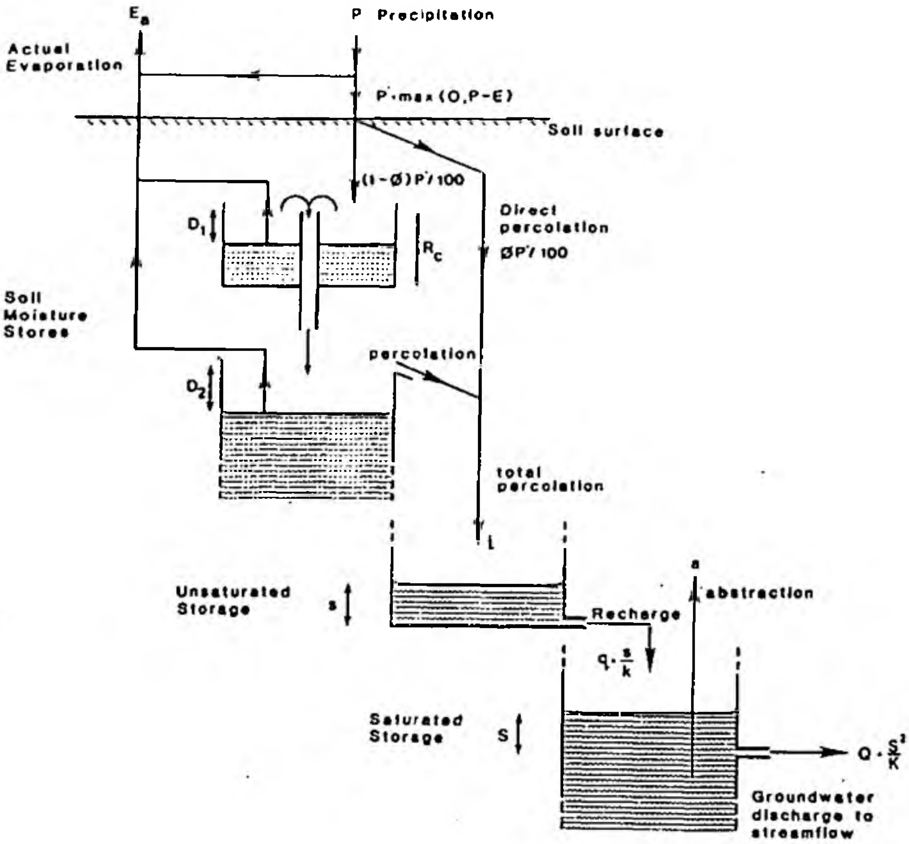


Figure 3.2.1 Representation of a hydrological response zone within the Thames Conceptual Model

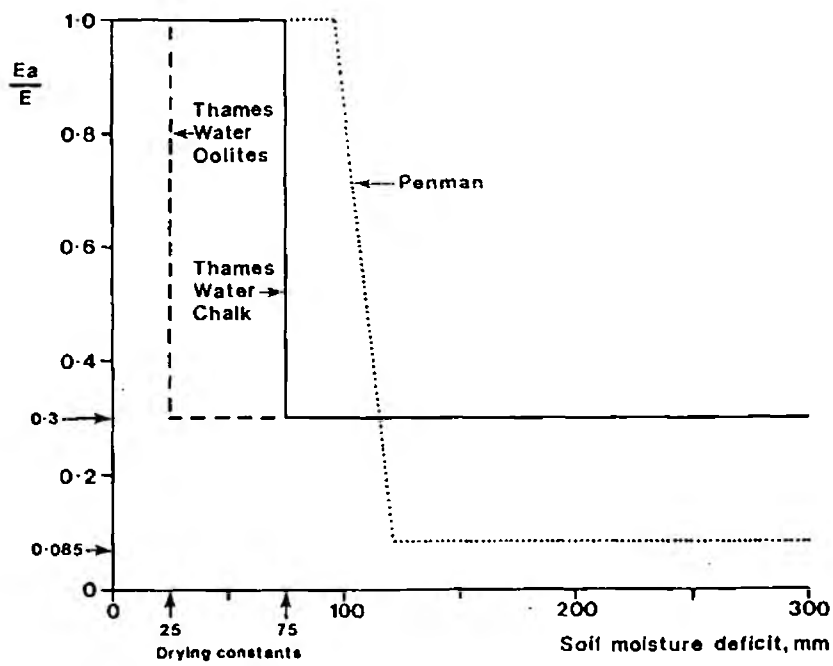


Figure 3.2.2 Representation of actual evaporation, E_a, as a function of potential evaporation, E, and soil moisture deficit

background of nonlinear storage models is given in Annex A.

The outflow from this lower groundwater store contributes to basin runoff. Total basin runoff derives from the sum of the groundwater flows from each zonal component of the model, including a constant contribution from an effluent zone if included in the model. A more recent extension of the model incorporates an additional channel flow routing component if required. This component of the model derives from the channel flow routing model developed by the Institute of Hydrology (Moore and Jones, 1978, Jones and Moore, 1980) in its basic form which employs a fixed kinematic wave speed. The model employs a finite difference approximation to the kinematic wave model with lateral inflow

$$\frac{\partial Q}{\partial t} + c\,\frac{\partial Q}{\partial x} = cq \qquad (3.2.1)$$

such that the flow at time t out of the n'th sub-reach is given by

$$Q_t^n = (1-c)\,Q_{t-1}^n + c\left(Q_{t-1}^{n-1} + q_{t-1}^n\right) \qquad (3.2.2)$$

where c is the kinematic wave speed and q_t^n is the lateral inflow to the n'th sub-reach. This model is used to represent routing of flows through a reach sub-divided into N sub-reaches, with both N and c controlling the attenuation of the flood wave through the reach.

The details of the reservoir storage calculations used in the Thames Conceptual Model are given below, first for the linear storage and then for the quadratic storage.

Linear reservoir

The function defining outflow, q, from the linear reservoir is

$$q = \frac{1}{k}\,s, \qquad (3.2.3)$$

where s is the volume in storage and k is a constant (with units of time).

For a time interval {t-T,t} at the start of which the outflow is q_{t-T}, and during which there is a constant input (flow from the soil zone) of i_t, it can be shown that the mean outflow during the period is given by

$$\bar{q}_t = \frac{k}{T}\left(1-\exp(-T/k)\right)q_{t-T} + \left\{1-\frac{k}{T}\left(1 - \exp(-T/k)\right)\right\}\,i_t. \qquad (3.2.4)$$

The final outflow, q_t, is given by

$$q_t = \exp(-T/k)q_{t-T} + \left(1-\exp(-T/k)\right)i_t. \qquad (3.2.5)$$

The calculations are normally performed with i_t and q_t in units of mm/day or mm/hour. To obtain a flow rate it is necessary to multiply by the area of the zone being considered.

Quadratic reservoir

The function defining outflow, Q, from the quadratic reservoir is

$$Q = \frac{1}{K} S^2, \tag{3.2.6}$$

where S is the volume in storage, and K is a constant (with units of volume time).

The net inflow into this storage, I, is the difference between mean outflow $\bar{q}$ from the linear reservoir and any abstraction, a. It is possible to derive analytical solutions for the outflow Q_t at the end of a time interval (t-T,t), during which the net inflow is I_t (assumed constant over the interval) and the initial outflow is Q_{t-T}.

To find Q_t, the differential equation to be solved is

$$\frac{dS}{dt} = I - \frac{S^2}{K}. \tag{3.2.7}$$

Using the transformed variable, $v = S/\sqrt{(IK)}$, the differential equation may be written

$$\frac{1}{1-v^2}\, dv = \sqrt{(I/k)}dt, \tag{3.2.8}$$

with solution

$$\tanh^{-1} v_t = \tanh^{-1} v_{t-T} + \frac{\sqrt{I_t}}{K} T, \tag{3.2.8}$$

where $v_t = S_t/\sqrt{(I_t K)} = \sqrt{(Q_t/I_t)}$. Taking hyperbolic tangents, and letting $\tau = \sqrt{(I/K)}T$ gives the result

$$Q_t = I_t\, (\sqrt{(Q_{t-T}/I_t)} + \tanh\tau)^2/(1+\sqrt{(Q_{t-T}/I_t)}\tan\tau)^2. \tag{3.2.9}$$

If I_t is negative due to abstractions exceeding recharge then a valid solution may be sought using the transformed variable $v = S/\sqrt{(-IK)}$, which gives the differential equation

$$\frac{1}{1+v^2}\, dv = -\sqrt{(-I/K)}\, dt, \tag{3.2.10}$$

with solution

$$\tan^{-1} v_t = \tan^{-1} v_{t-T} - \sqrt{(-I/K)}T, \tag{3.2.11}$$

where $v_t = S_t/\sqrt{(-I_t K)} = \sqrt{(Q_t/(-I_t))}$. This yields the result

$$Q_t = I_t \tan^2\left\{\tan^{-1}\sqrt{(Q_{t-T}/(-I_t))} - \sqrt{(-I/K)T}\right\}. \tag{3.2.12}$$

Note that in this case flow will cease at time

$$T' = \sqrt{(K/(-I_t))} \tan^{-1} \sqrt{(Q_{t-T}/(-I_t))} \qquad (3.2.13)$$

when the expression in curly brackets in Equation (3.2.12) falls below zero and a volume deficit begins to build up, which at the end of the interval (t-T,t) is

$$V_t = I_t(T-T'). \qquad (3.2.14)$$

The solution for I = 0 may be readily obtained by solving the differential equation

$$\frac{dS}{dt} = -\frac{S^2}{K} \qquad (3.2.15)$$

which yields the result

$$Q_t = (1/\sqrt{Q_{t-T}} + t/\sqrt{K})^{-2}. \qquad (3.2.16)$$

A summary of the model parameters used in the Thames Catchment Model is presented in Table 3.2.1 together with the units used in the IH implementation of the model.

Table 3.2.1 Thames Conceptual Model Parameters and Stores

Parameter or Store	Description	Thames unit	IH unit	Ratio: IH/Thames
A	Area	km^2	km^2	1
R_c	Drying constant	mm	mm	1
ϕ	Direct percolation factor	%	fraction	1/100
k	Linear reservoir time constant	days	hours	24
K*	Quadratic reservoir time constant	$(m^3sec^{-1})day^2km^{-2}$	mm hours	2073.6
a	Abstraction	Ml/day	cumecs	1/86.4
q_c	Effluent	Ml/day	cumecs	1/86.4
D_1	Deficit of upper soil moisture store	mm	mm	1
D_2	Deficit of lower soil moisture store	mm	mm	1
q_0	Linear reservoir outflow	mm/day	mm/hou r	1/24
Q_0	Quadratic reservoir outflow	Ml/day	mm/hou r	1/(24*area)
Q_n	Routed flows	Ml/day	cumecs	1/86.4

3.3 The Isolated Event Model

The Isolated Event Model, or IEM, was originally developed for design applications as part of the UK Flood Studies Project (NERC,1975). In many respects it is very similar to the single zone representation of the Thames Conceptual Model in using the Penman stores concept and a quadratic reservoir for routing. However, the use of the Penman stores concept is not done as part of an explicit soil moisture accounting procedure as is the case with the TCM. Rather the soil moisture deficit it provides is used as an indicator of catchment wetness within an empirical equation which relates the proportion of rainfall that becomes runoff (the runoff coefficient, f)) to the soil moisture deficit, D. Specifically the exponential function

$$f = \alpha \exp(-\beta D) \qquad (3.3.1)$$

is used where β is a parameter with units (mm water)$^{-1}$ and α is a dimensionless parameter. Note that the IEM uses as standard a Penman upper store of depth 75mm, the root constant for short grass, with no bypassing ($\phi=0$). Because the original formulation was event-based and for design the runoff coefficient, f, was applied to the whole storm and D was the soil moisture deficit at the start of the storm. The parameter α can be interpreted as a "gauge representativeness factor" since with zero deficit (saturated conditions) a proportion α of the rain becomes runoff.

In the IEM approach the storm rainfall time series is multiplied by the factor f to give an "effective rainfall" series. This is then used as input to the quadratic storage reservoir and the hyperbolic form of the solution (Equation 3.2.9) used to calculate the outflow from the reservoir. This outflow, delayed by a chosen amount, forms the IEM model flow prediction.

In real-time flood forecasting applications the concept of an "event" is often an awkward notion to work with. It becomes more natural then to define f as a time variant function of the deficit D, maintained as a water balance calculation throughout the storm. Thus we have

$$f_t = \alpha \exp(-\beta D_t). \qquad (3.3.2)$$

The calculation of D_t throughout the storm can be achieved using the Penman stores employed within the Thames Conceptual Model, and indeed can be calculated continuously between events. In practice the latter is most easily achieved (at least in off-line model calibration mode) using daily rainfall data and a daily time step, changing to the smaller interval of the flood event data at the start of each event. Note that in the IEM model formulation no use is made of the outflows from the Penman stores, only the deficit as an index of catchment wetness and its impact on the ensuing volume of flood runoff. In many respects its use was as an engineering expedient at a time when continuous rainfall records were not widely available at the Institute of Hydrology and the soil moisture deficit calculated routinely at the Meteorological Office provided a readily available, and succinct, source of information on the antecedent conditions of selected flood events. In the 1990's there is no real justification for keeping these modelling components separate. It is also more attractive to use the Penman stores concept as part of an integrated, explicit water account model, as is done in the TCM, rather than through invoking an empirical function to account for "losses" as is the case with the IEM. However, whilst it may be more attractive it does not necessarily ensure superior forecast performance and it is one of the purposes of this study to assess the accuracy of the forecasts from the two models.

3.4 The Probability Distributed Model

The Probability Distributed Model or PDM is a fairly general conceptual rainfall-runoff model which transforms rainfall and evaporation data to flow at the catchment outlet. Figure 3.4.1 illustrates the general form of the model. Runoff production at a point in the catchment is controlled by the absorption capacity of the soil to take up water: this can be conceptualised as a simple store with a given storage capacity. By considering that different points in a catchment have differing storage capacities and that the spatial variation of capacity can be described by a probability distribution, it is possible to formulate a simple runoff production model which integrates the point runoffs to yield the catchment runoffs to yield the catchment runoff.

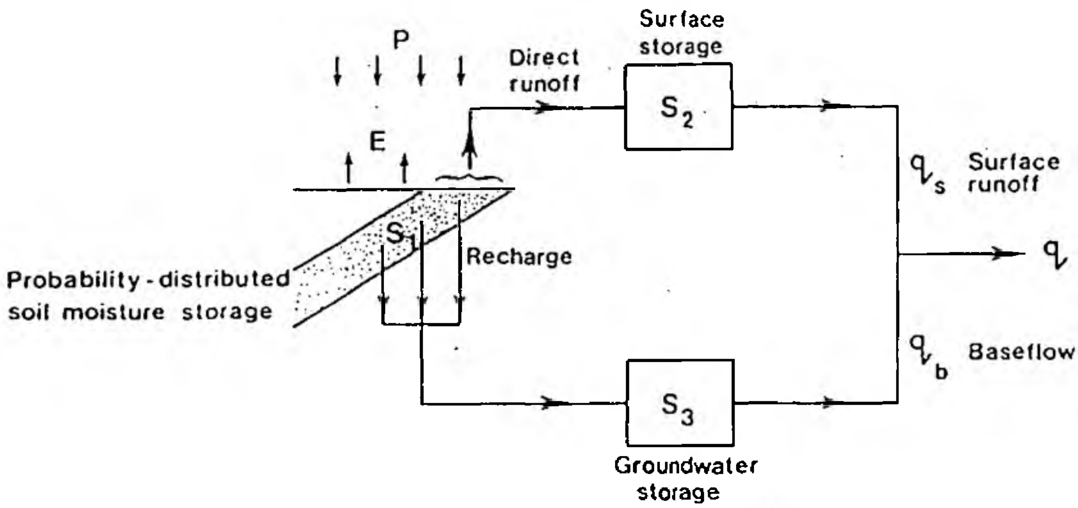


Figure 3.4.1 The PDM rainfall-runoff model

The probability-distributed store model is used to partition rainfall into direct runoff, groundwater recharge and soil moisture storage. Direct runoff is routed through a "fast response system", representing channel and other fast translation flow paths. Groundwater recharge from soil water drainage is routed through a "slow response system" representing groundwater and other slow flow paths. Both routing systems can be defined by a variety of nonlinear storage reservoirs or by a cascade of two linear reservoirs (expressed as an equivalent second order transfer function model constrained to preserve continuity). A variety of spatial distributions of store depth are available fo define the probability-distributed store model. Alternatively the store model can be replaced by a simple proportional splitting rule for partitioning rainfall to follow surface and subsurface translation paths. A constant background flow can be included to represent compensation releases from reservoirs, or constant abstractions if negative.

The model is specifically tailored for real-time application. Facilities exist to correct the model forecasts in real-time, either by modifying the water contents of the conceptual stores or by augmenting the forecasts with an error predictor. Further details of the model structure deployed are contained in Moore (1985, 1986) and Annex A.

3.5 The Synthetic Unit Hydrograph Model

The Synthetic Unit Hydrograph Model, or SUHM, is based on a time area diagram concept and a cascade of linear storages to represent advection and attenuation in the translation of "runoff" to the basin outlet. Runoff production ("effective rainfall" generation) is based on a discrete form of distributed store model, analogous to the continuous distributed store functions used in the PDM model.

For urban catchments a zonal concept is involved in which the three types of zone

(i) impervious or paved area (roofs, roads, etc.)
(ii) riparian open area (parks, playing fields, etc.)
(iii) other open areas (backgardens, etc.)

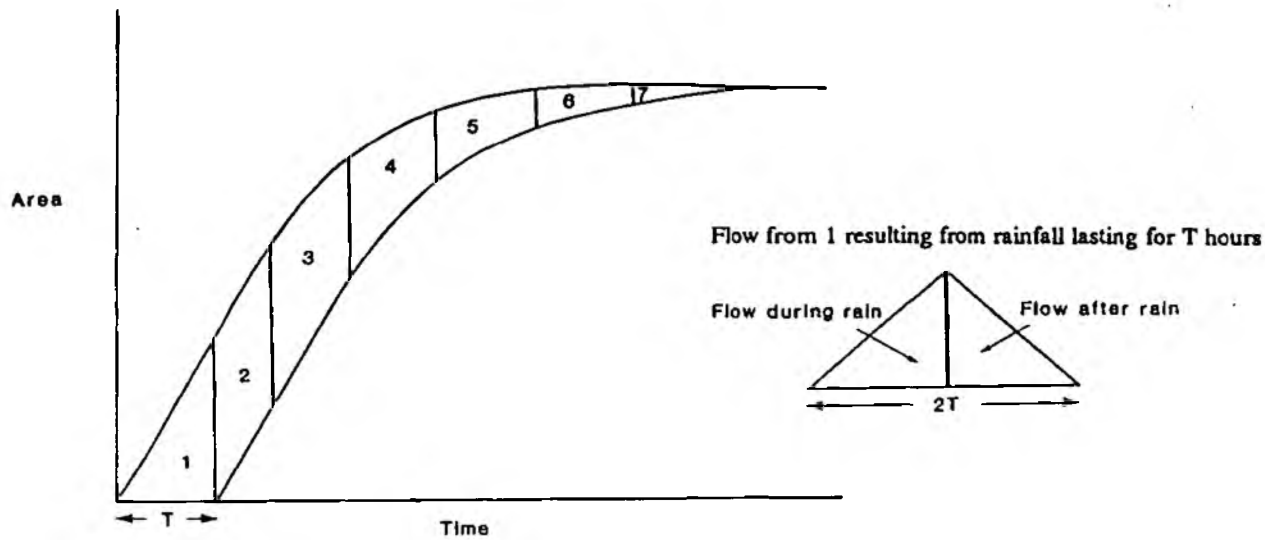
are identified and treated independently, being added at the end to form the total catchment hydrograph. An outline of the translation and runoff production representations used in each zone of the SUHM is presented in the remainder of this sub-section.

The translation function

The time area diagram method of translation essentially involves the derivation of isochrones for the catchment, that is lines joining points of equal time of travel to the basin outlet. Runoff from a sub-zone defined, for example, between 0 and the T hour isochrone will begin to appear at the basin outlet immediately and will increase linearly to a peak at T hours and then decrease linearly to zero after 2T hours. In practice the response is attenuated by passing it through a linear reservoir. A similar triangular response profile with a 2T time base occurs for runoff generated in the sub-area between the nT and (n+1)T isochrones. Attenuation in this case is achieved by passing the triangular pulse through a cascade of n linear reservoirs. The calculation of isochrones is based on measured distances and invoking a velocity of travel and a time of entry. The process is illustrated in Figure 3.5.1. Manning's equation is used to calculate the velocity in pipe, channel and overland pathways; this process is quite complex and demands a variety of forms of survey data and assumptions regarding appropriate roughness factors to use. The effect of additional storage in the form of lakes, reservoirs and washlands may also need to be taken into account.

Attenuation of the runoff, as previously mentioned, assumes a simple linear storage function operating within each isochrone "band", such that outflow from the band, q, is related to storage, S, such that q = kS, where k is an attenuation factor or in reciprocal form a reservoir time constant. Thus for the (0,T) time band, its impulse response function is

(a) T-hour time area diagram



(b) Cascade of linear reservoirs

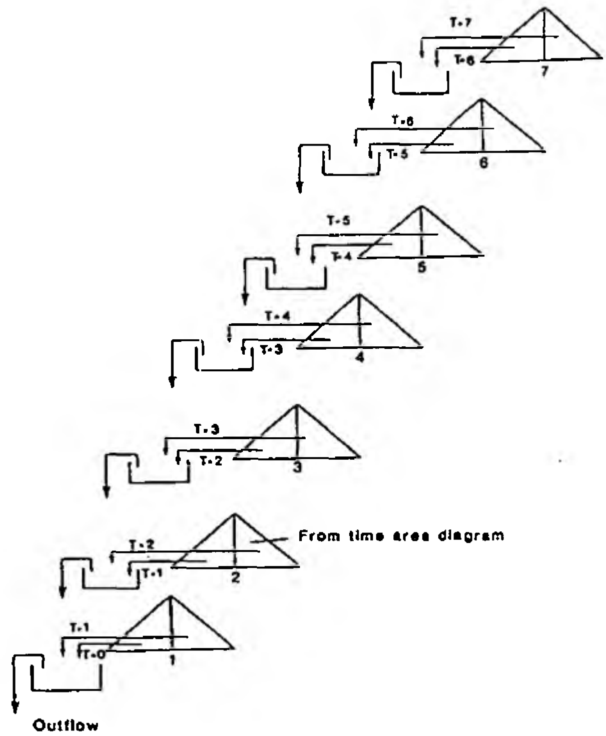


Figure 3.5.1 Translation component of the SUHM model

$$u_1(0,t) = \frac{1}{k}\exp(-t/k). \qquad (3.5.1.)$$

For the n'th isochrone band {(n-1)T,nT} the impulse response is that for a cascade of n linear reservoirs i.e.

$$u_n(0,t) = \frac{1}{k\Gamma(n)}\left[\frac{t}{k}\right]^{n-1}\exp(-t/k) \qquad (3.5.2)$$

where Γ(n) is the gamma function. The corresponding step response, due to a constant uniform unit input, is the well-known S-curve

$$S(t) = \frac{1}{k\Gamma(n)}\int_0^t\left[\frac{t-\tau}{k}\right]^{n-1}\exp\left[-\frac{(t-\tau)}{k}\right]d\tau \ . \qquad (3.5.3)$$

This allows the T-hour response for a cascade of n linear reservoir to be calculated as

$$u_n(T,t) = \{S(t)-S(t-T)\}/T \ . \qquad (3.5.4)$$

This is used to spread an input for a time-interval of T hours into an attenuated input, beginning at the same time but extending for nT hours into the future.

The Runoff Production Function

Up to now the focus has been on translation of runoff to the basin outlet and the representation of advection and attenuation processes in the SUHM model. The generation of runoff at a point within the basin, prior to translation, will be considered next. Losses due to interception, for example by trees, and through detention storage are considered together. In a similar way to the PDM model a spatial distribution of storages is assumed. However, rather than use a continuous parametric distribution form a discrete non-parametric form of distribution is employed. The paved catchment is assumed to be made up of 5 equal areas (i.e. each occupying 20% of the paved catchment area) with the ratios of the storage in each zone chosen to be 1:4:9:16:25 with the smallest having a value, D_p, typically equal to 0.4 mm. The riparian open area is made up of 6 equal areas with storages in the ratio 1:4:9:16:25:36 with the smallest having a value, D_g, typically equal to 0.6 mm. The implied distribution functions, indicating the proportion of the paved or riparian catchment having storage depths below a given amount, are shown in Figure 3.5.2. Evaporation is taken into account in a conventional manner within these calculations.

Whereas detention and interception losses are accounted for together over paved and riparian areas, losses are considered due to infiltration over the open area part of the catchment. The infiltration model used is a modified form of the Horton and Holton model in which the

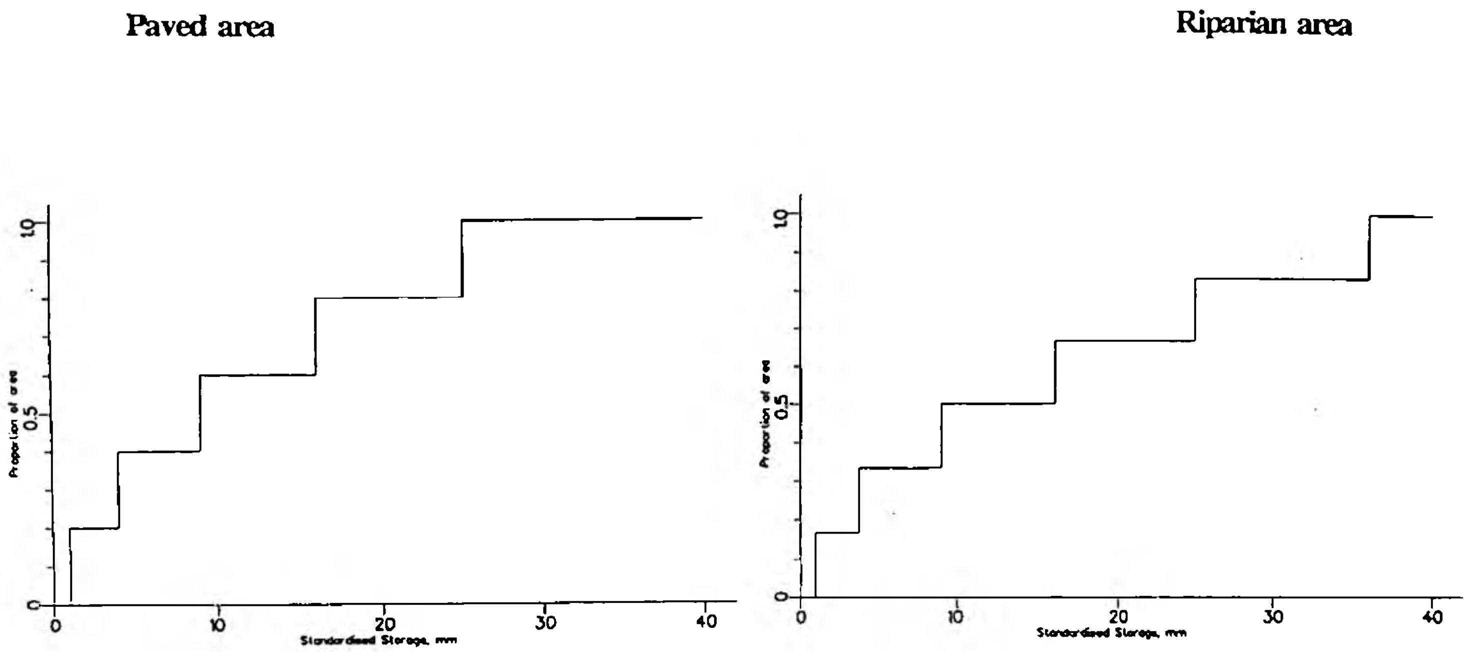


Figure 3.5.2 **Runoff production component of the SUHM model: distribution functions of storage capacity, in standardised form, used for paved and riparian areas**

infiltration rate

$$f = f_{max}\left\{ a + (1-a)\left[1 - \frac{F}{F_{max}} \right]^{n} \right\} \qquad (3.5.5)$$

where F is the soil moisture content of a soil with capacity F_{max}, f_{max} is the initial rate of infiltration and a and n are constants for a particular soil in a given condition. It is also assumed that $F_{max} = \kappa f_{max}$ where again κ is a soil constant. This relation implies an infiltration rate varying from a minimum value of af_{max} at saturation to a maximum value for a dry soil of F_{max}. Typically a equals 0.95, n is set to unity and κ chosen to be 6 hours.

Further details of the SUHM model are given in Greater London Council (1984).

4. FLOOD FORECASTING MODEL DEVELOPMENT

4.1 Introduction

The main area of model development has been the implementation of the TCM and IEM within the framework provided by the IH time-series model calibration and assessment software. Minor modifications have been made to the PDM, and the SUHM has yet to be implemented.

The calibration and assessment software has recently been ported on to the IH network of UNIX workstations, from which it accesses a database server on the VAX. The superior response and graphical display available from the Silicon Graphics IRIS Indigo workstation has enabled the addition of a facility for interactive parameter adjustment which should provide a valuable complement to the existing automatic optimisation procedure.

4.2 Thames Conceptual Model

The Thames Conceptual Model has been implemented at IH as a PSM (Penman Soil Moisture) rainfall-runoff model, operating within the existing calibration and assessment software.

This implementation presently lacks some of the functionality of the Thames implementation of the hourly-based BASIC program FLUD2; these are listed below:

i) Zoning of rainfall, and averaging of rainfall from different stations, are not yet supported. The design of this facility has implications for other models within the calibration system, and is a priority for software development.

ii) Effluents and abstractions have constant, rather than monthly, values. This does not appear to be a problem for the catchments to be modelled in this Study.

The new facilities provided by the IH software comprise:

i) Automatic optimisation of all model parameters for single or multiple events.

ii) 15-minute time step, with multiples thereof in order to simulate the operation of an hourly-based model.

iii) A pure time delay between rainfall and runoff.

iv) A variety of non-linear reservoir options (quadratic storage are standard).

v) Time-series of potential evaporation data.

vi) Use of a forecast rainfall series to construct forecast flows.

vii) Error-prediction for forecast flows using ARMA or logarithmic ARMA prediction of the error series.

Incorporation of facilities for state-correction within the TCM are planned.

The units of the parameters and flows in the PSM model differ from those used in the Thames model implementation and have been summarised, with factors for conversion, in Table 3.1.

The equivalence of the IH and Thames implementations of the model (for an hourly time step) was tested for 3 of the 4 events at Uxbridge and 5 of the 6 events at Kinnersley Manor. A visual comparison between the IH model hydrographs and the plots supplied by NRA Thames Region demonstrates equivalence for some events, and differences for others, as summarised in Table 4.1.1 below. Inconsistencies between the parameter sets and model results supplied by Thames appear to be the main cause of these discrepancies.

Table 4.1.1 Results of a visual comparison of NRA and IH model results

Event	Comment
(a) Pinn at Uxbridge	
4 Jan 1990 - 11 Jan 1990	No difference
25 Jan 1990 - 1 Feb 1990	No difference
8 Feb 1990 - 15 Feb 1990	No difference if 0.01 is used instead of 0.03 for cqn ($K^* = 2073.6$ cqn)
25 Oct 1990 - 1 Nov 1990	SMD file missing, comparison not possible
(b) Mole at Kinnersley Manor (using c = 0.4 instead of c = 0.2)	
4 Jan 1990 - 11 Jan 1990	No difference
18 Jan 1990 - 25 Jan 1990	Slight differences attributed to hourly vs. 15-minute rainfall differences
8 Feb 1990 - 15 Feb 1990	Slight differences of unknown origin, possibly rainfall
25 Oct 1990 - 1 Nov 1990	Substantial difference probably due to extra rain in 15-minute data relative to hourly data.

4.3 The Isolated Event Model

The Isolated Event Model, or IEM, is implemented within the PSM model. Two modes of operation are possible. In the first mode, which emulates the operation of the Thames IEM code, the runoff coefficient is treated as a single parameter, fixed for the duration of the event. No soil moisture accounting is required, and the IEM is invoked as a special case of the PSM model with the following options:

i) a single hydrological response zone;

ii) zero potential evaporation (an unnecessary restriction);

iii) zero drying constant or, equivalently, 100% direct percolation;

iv) zero linear reservoir time constant (total bypassing); and

v) zero channel flow routing reaches.

In the second mode, Penman soil moisture accounting is carried out, but does not lead directly to runoff. Instead, the combined soil moisture deficit is used in equation 3.3.2 to calculate a runoff coefficient which can vary over the course of an event, and between events. Options are as above, with the exception of a non-zero drying constant.

The rainfall smoothing facilities provided within the Thames IEM code are not currently available, but are to be implemented as a separate module.

4.4 Probability-Distributed Model

The facility to use forecast rainfall to construct the forecast flow has been implemented. Minor modifications have been made to permit missing values in the observed flow, and to provide for optimisation of the pure time delay as a real-valued parameter. Inclusion of a facility to derive rainfall as a weighted average of values from more than one rainfall station is planned.

4.5 Synthetic Unit Hydrograph Model

The SUHM is not yet implemented. Its use will be limited to two urban catchments: Beverley Brook at Wimbledon Common and Silk Stream at Collindeep Lane.

5. RAINFALL FORECASTS

5.1 Introduction

The principal object of this study is to assess the usefulness of Local Radar and Frontiers rainfall forecasts in operational flood forecasting. The construction and format of these two types of radar-derived rainfall forecast are briefly summarised in the following two sections. Both forecasts are areally distributed over the squares of a radar grid, and catchment averages must be derived for use by the flood forecasting models, as described in Section 5.4. Finally, there is an operational requirement for alternative rainfall forecasts or profiles to supplement or replace missing radar-derived forecasts. Such a forecast might also provide a convenient baseline from which to measure the performance of the radar-derived forecasts, and a number of possibilities are mentioned in Section 5.5.

5.2 Local Radar Forecasts

Local radar forecasts are generated by advecting the observed, uncalibrated radar rainfall field using a velocity field derived by comparison of two successive radar images. The procedure is fast and automatic, and full details may be found in the Final Report on the London Weather Radar Local Rainfall Forecasting Study. The option of smoothing the grid-square forecasts towards the field-average value with increasing lead time is used for this study, as it appears to yield the best results. Overall, the rainfall forecasting study concluded that individual local forecasts were as good or better than the corresponding Frontiers forecasts up to a lead time of around two hours.

In operational use, local forecasts would be generated at the flood forecasting centre on arrival of the radar data, and forecast 15-minute accumulations would be available to the flood forecasting model within 5 minutes of the rainfall forecast origin. For the purposes of this study, local forecasts are generated as required using the radar rainfall images supplied from the VAX archive at Waltham Cross.

5.3 Frontiers Forecasts

Frontiers is a radar and satellite based rainfall forecast product supplied by the Meteorological Office. Observed rainfall fields can be advected by velocity fields derived from a variety of sources, and a considerable degree of operator intervention may be involved. Each accumulation forecast comprises 15-minute accumulations on a 5km grid for lead times up to 6 hours, and a new forecast is generated every half an hour. Further details may be found in the Final Report on the Evaluation of Frontiers Accumulation Forecasts in the NRA Thames and North West Regions.

In operational use, Frontiers forecasts are usually available at the flood forecasting centre approximately 40 to 50 minutes after the time origin to which they relate.

Frontiers forecasts from October 1990 onwards have been provided on tapes from the VAX archive at Waltham Cross. Failures in the Frontiers system mean that for the only period so far examined, 25-30 October 1990, approximately 30% of the expected forecasts are missing. It is anticipated that the reliability of the system will be greater for more recent events.

5.4 Catchment Averaging

15-minute accumulations from the Local Radar and Frontiers forecasts, on 2km and 5km grids respectively, are averaged using the same digitised catchment boundaries and raster scanning algorithm as for the observed radar accumulations described in Section 2.4. A difference arises for the Local Radar forecast in that the edge of the field may be advected past the catchment boundary, resulting in missing values at some or all grid squares. The average rainfall is computed over the reduced area, with the facility to flag the catchment forecast as missing if the coverage drops to a given threshold value (currently zero).

Catchment-average rainfall forecast files are generated in a single pass of the Local Radar Forecasting program, which picks up both Frontiers forecast and local radar data, computes the local forecast, and performs catchment averaging of both forecasts.

5.5 Baseline Forecasts

Possibly the simplest option for an automatic baseline forecast is persistence of the latest available observed (or forecast) rainfall. A simple variant might involve tapering to zero, to some other fixed value, or to some average over past rainfall. In a real-time situation the operator might also have the facility to make an ad hoc selection amongst typical rainfall profiles based upon experience and interpretation of the developing weather system. A suitable baseline forecast for this study has not yet been chosen.

6. EVALUATION OF COMBINED RAINFALL AND FLOOD FORECASTS

6.1 Introduction

The earlier sections of this report have described the progress made in developing the data and software base for the evaluation of combined rainfall and flood forecasts. This section sets out a strategy for evaluation, and explains some of the important terms and concepts involved.

The evaluation process is divided into three main phases - Calibration, Forecasting and Assessment - described in sections 6.2 to 6.4. These are followed by an illustration of some aspects of the evaluation, using one model for one catchment to assess the effect on flood forecasting performance of using three different types of forecast rainfall.

6.2 Calibration Phase

Definition of models

A number of rainfall-runoff models will be constructed for each of the catchments in the study. Each model is defined, at increasing levels of detail, by its type (TCM, IEM, PDM, SUHM), structure (number of zones, type of probability distribution, etc.) and the values of its parameters. (This distinction between levels is partly a matter of convenience - both TCM and IEM type models are implemented within the PSM model structure.) Moreover, each model may have one or more **operating modes**, depending on the use made of observed flows.

Operating modes

If observed flows are not used, except for initialisation, the model is said to be operating in **simulation mode**, acting as a function which transforms rainfall and evaporation to river flow. A model which has been calibrated in simulation mode may be extended to use observed flows by addition of further structure and associated parameters. These might take the form of rules for adjusting model states (**state-correction mode**) or predicting future errors (**error-prediction mode**). The former are heavily dependent on the structure of the simulation mode model, whilst the latter are essentially independent. Parameter-adjustment is not considered in this study, since the view is taken that parameter variability is best addressed through improving the structural form of the model rather than tracking its variation in real-time. A model incorporating observed flows either through state-correction or error-prediction will be said to be operating in **updating mode**.

Calibration procedure

Calibration of a model is achieved by comparison of observed and model hydrographs for one or more flood **events**. It may comprise a mixture of manual adjustment, requiring an understanding of the physical basis of the models and visual inspection of the model hydrograph, and automatic optimization aimed at minimising an **objective function** which provides a measure of the difference between observed and simulated flows. The objective function used in this study is the root mean square of the differences between observed and simulated flows at each time step, with provision to exclude a warm-up period and flows outside a given range. In updating mode, the individual errors at each time-step are based on the deviation from the current observed flow of an updated forecast which uses observed flows up to the previous time-step (the **one-step-ahead error**).

For a given model type, catchment, and source of rainfall data, the procedure is as follows.

1. Choose a set of events, bearing in mind that it is desirable to keep calibration events separate from evaluation events, and to use a common set of events where possible.

2. Choose a model structure and initial parameter values.

3. Adjust parameter values interactively and/or automatically, operating the model in simulation mode, to arrive at an optimum set.

4. Repeat 2 and 3 with different structures to give the best model performance when assessed in simulation mode.

5. Choose an additional structure to give state-correction or error-prediction.

6. Carry out automatic optimization of the parameters defined in step 5 using the one-step-ahead error.

7. Repeat 5 and 6 using different structures to give the best overall model.

Models to be calibrated

Three types of model, the TCM, IEM and PDM, have been selected for evaluation using data from each of 8 catchments; a fourth model, the SUHM, will be calibrated on only two of the catchments (for which it has been previously calibrated). The relative merits of different structures within each model will only be considered during calibration, with a single structure going on to the forecasting phase. Both state-correction and error-prediction will be considered for use with each type of model, although it may be that only one form for each model will be carried through to the forecasting phase. The only remaining variable is the source of rainfall used for the calibration. The principal distinction is between observed radar and raingauge data, giving rise to two possible sets of parameter values for each catchment model. Special consideration will be given to locally calibrated radar data for those catchments served operationally by this system. Variations on the number and weighting of different raingauges will be avoided. The type of rainfall forecast to be used has no effect on the calibration.

6.3 Forecasting Phase

In the forecasting phase, the calibrated models will forecast flows during selected events using different types of rainfall forecast and operating modes. Before going on to examine how these forecasts are constructed, it will be useful to review some of the terms used in this discussion.

Terminology

A **forecast value** is an estimate of the value of an observable quantity (rainfall or flow) at some future time (the **forecast time**) usually constructed from the time of the last observed value of that quantity (the **forecast origin**). The difference between these two times is the **lead time**. The combination of rainfall and flow forecasts provides a possible source of confusion, since the origins of each type of forecast may be different, and unless otherwise stated the above terms will be taken to apply to the flow forecast. In an operational setting, the time at which observed or forecast values become available may be important, but this delay will not be considered explicitly here.

A **forecast series** (or more simply, a **forecast**) is a sequence of forecast values having an increasing forecast time. Two types of forecast will be examined.

A **fixed-origin, variable lead-time forecast** is a forecast series having a common forecast origin. The number of forecast values it contains will be dictated by the time interval of the forecast and the maximum lead time specified. If such forecasts are constructed at every time-step then the forecast series formed from values with the same lead time is called a **fixed lead-time forecast.** It is well-suited to the formation of pooled statistics which describe the typical performance of a model for particular lead times. The one-step-ahead forecast series is a particularly important special case, since the absence of dependence in its error series indicates that no further improvement can be achieved.

Forecast construction

The availability of Frontiers forecasts through an event is variable, and at best they are constructed every half an hour. Local radar forecasts for lead-times up to 6 hours can be constructed from every 15-minute time-origin for which radar data are available. As mentioned above, these forecasts are assumed to become available for use by the flow forecasting models as soon as their forecast origin is reached. A baseline forecast, to be used as a frame of reference, will be incorporated in the evaluation.

For all flow models and operating modes, flow forecasts at every time origin during an event are constructed from the most recent data (observed or forecast) having the same or earlier time origin. These fixed-origin forecasts will extend to a lead time of at least 6 hours. Apart from the lack of delay, this procedure is intended to match the operational procedure as closely as possible.

Fixed lead-time forecasts are constructed by selecting values at the appropriate lead-time from each of the fixed-origin forecasts. It is worth remembering that while these values have a common lead-time with respect to the time of the latest observed rainfall (no missing rainfall is allowed in the evaluation events), they may have different lead-times relative to the latest observed flow (if some observed flows are missing) and also relative to the latest available rainfall forecast origin.

Events for evaluation

A common set of events are to be used for the evaluation of all models; events used for calibration are to be excluded from this set.

6.4 Assessment Phase

This phase comprises measurement of the performance of individual forecasts, analysis of the factors that determine forecast performance, and pooling of performance statistics in order to draw conclusions as to the relative merits of different flow models and rainfall forecasting methods. The assessment phase is conceptually separate from the other phases although, in practice, measurements of forecast performance are made during the forecasting phase, and it is the factor analysis that determines exactly which models are to be calibrated and which forecasts are to be generated.

Measures of forecast performance

The most obvious and intuitive measure of forecast performance is a plot of the forecast and observed hydrographs. Such plots will undoubtedly play an important role in illustrating the main features and conclusions of this study, but they cannot be pooled for further analysis. Simpler measures, yielding only one or a few values per forecast, are required.

For a fixed-origin forecast, these might include the magnitude (expressed as a percentage of the observed) and timing error in predicting a hydrograph peak, failure or success in predicting an alarm level, and whether or not a false warning would be generated. These measures obviously depend strongly on the exact form of the hydrograph and the alarm levels for the gauging station, and are consequently difficult to pool across events and stations.

For a fixed lead-time forecast, alarm level measures can also be applied. However, straightforward root mean square error and R^2 goodness-of-fit measures are universally applicable and easily pooled. Whilst such measures of performance are likely to dominate the assessment phase it will be important to ensure that peak and/or alarm level measures are properly considered when drawing final conclusions.

Factor analysis of forecast performance

The factors which determine the value of a performance measure on a forecast series may be conveniently grouped into those which generate different calibrated models, those which require different runs of a calibrated model, and those which generate different forecasts within a run.

If the two SUHM models are treated as separate cases, then the calibrated models are completely factored into

Catchments(8) x Model Types(3) x Observed Rain Types(2) = 48 (+2)

and the forecasting runs are completely factored into

Models(50) x Modes(2) x Rainfall Forecasts(3) x Events(N) = 300N
{ x Observed Rain Types(2) = 600N}

where a common set of N events is assumed to be used for all catchments. It is likely that the observed rain type (raingauge or radar) used for a forecasting run will be the same as that for which the model was calibrated, so that it will not appear as a separate factor.

The fixed lead-time forecasts generated by each run may be factored by lead-time. Assuming that (say) 6 lead-times are of interest, this gives a total of 1800N forecasts, on each of which several performance measures may be made.

The fixed-origin forecasts generated by each run lack an obvious factor which has the same meaning across all runs. If a well-defined reference point, such as the main hydrograph peak or an alarm level exceedence, exists for most or all events, then an appropriate factor might be the time of the forecast origin relative to this reference point.

Pooled statistics

The factor analysis described above provides a highly structured form for the large number of raw results generated during the forecasting phase. The traditional tool for pooling and interpreting the results from a factored experimental design is Analysis of Variance (ANOVA). The assumptions implicit in this method are generally inappropriate for analysing the highly non-linear behaviour of rainfall-runoff models and the non-stationarity of their errors, but it may be possible to employ a similar non-parametric (or 'distribution-free') technique capable of performing significance tests. At a less sophisticated level, measures such as the root mean square error may be pooled (with care) across events, catchments and other factors, and presented graphically with respect to the factors of interest. A simple ranking serves to identify the 'best' model and type of rainfall forecast for a given performance measure.

6.5 Illustration of the Evaluation Process

The Thames Conceptual Model of the River Mole at Kinnersley Manor was chosen to illustrate the evaluation process because existing parameter sets were available and the catchment response is not particularly complicated, making calibration simpler. A single event was forecast to assess the effect of three types of rainfall forecast and two operating modes.

Calibration phase

A model was calibrated using rainfall data from Burstow raingauge and potential evaporation data for the Upper Mole. Six events were available for calibration, the fourth of which was also used for forecast assessment, although it is envisaged that in the full-scale study the assessment events would form a separate set from the calibration events.

Starting from one of the parameter sets supplied by the NRA Thames Region, but with a 15-minute time-step, automatic optimisation in simulation mode was used to obtain the best least-squares fit to the set of 6 events, as shown in Figure 6.5.1. The fit is good for most of the events, and in particular for the event to be forecast, but is poor for the sixth event. The use of purely automatic calibration resulted in parameter values such that model zones could no longer be readily identified with physical zones, and further manual calibration of this model may be appropriate.

An ARMA(3,0) time-series model structure was chosen for use in error-prediction mode, and its coefficients were calibrated automatically.

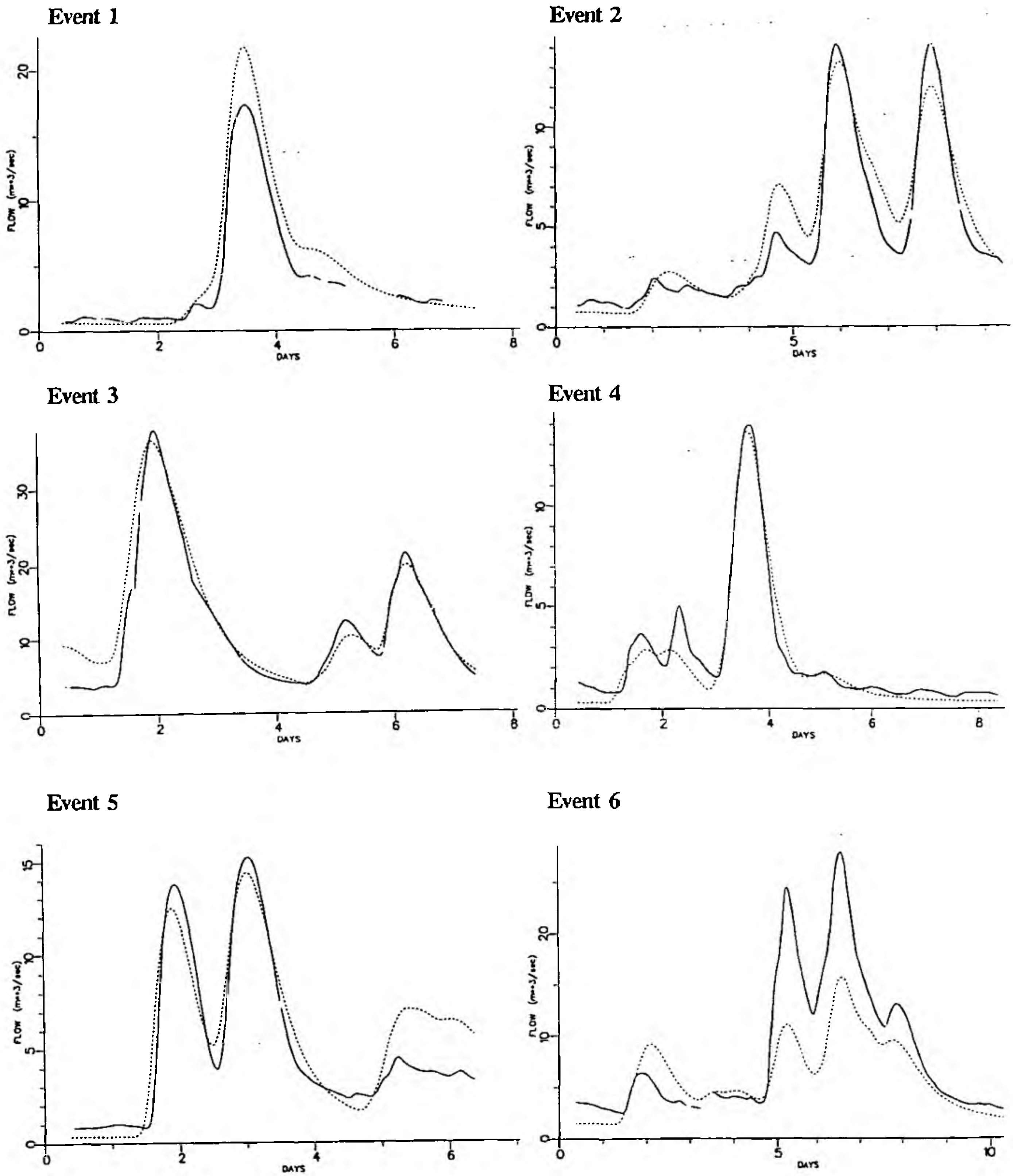


Figure 6.5.1 **Calibration results for the Thames Conceptual Model of the River Mole at Kinnersley Manor. Solid lines show observed flow, dashed lines show simulated flow.**

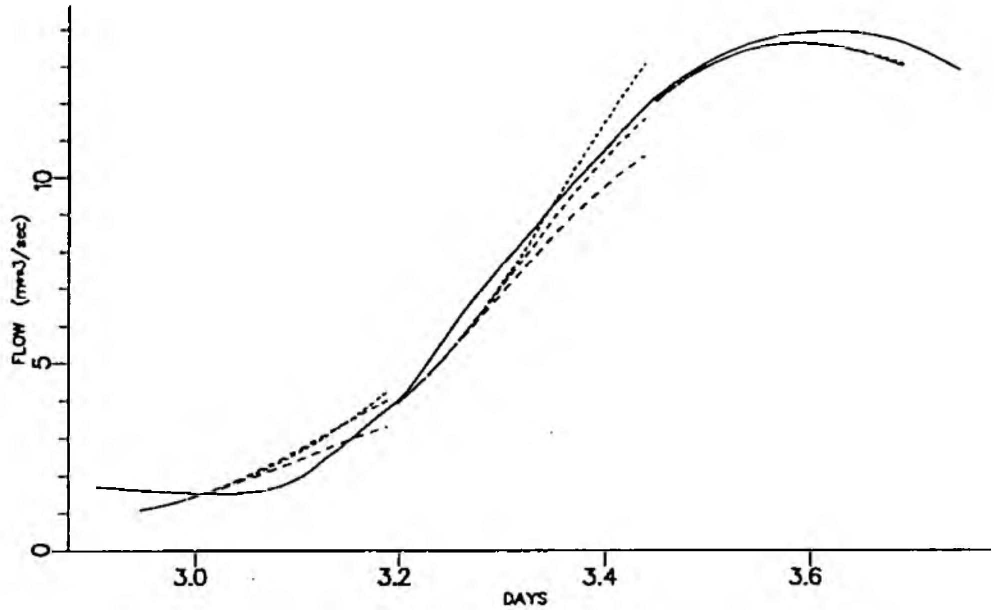
Forecasting phase

Flow forecasts for the event of 25-30 October 1990 were generated for each 15-minute time origin during this period with lead times up to 6 hours. The model was run in both simulation mode and error-prediction mode with three different forecast rainfall series: the observed radar rain, the local radar forecasts, and the Frontiers forecasts. The observed radar data, and hence the set of local radar forecasts, are complete. Statistics on the coverage of the local radar forecasts were not collected, although some coverage was always present. Approximately 30% of the possible Frontiers forecasts were missing, mostly in isolation or as short runs.

Assessment phase

The fixed-origin forecasts at 16, 10 and 4 hours before the main hydrograph peak are shown in Figure 6.5.2, and the 4-hour fixed lead-time forecasts in Figure 6.5.3. It is evident that the use of different types of rainfall forecast has only a minor effect on forecast performance. A simple R^2 goodness-of-fit statistic was used to evaluate the performance of the fixed lead-time forecasts at hourly lead-time intervals between one and four hours. This measure is plotted against lead-time in Figure 6.5.4, using a separate curve for each possible value of the other factors. It can be seen that within the modest range of variation due to the type of rainfall forecast, the local radar forecast performs better than the Frontiers forecast, with the observed radar rain giving the best performance, as might be expected. The overall lack of effect probably reflects the relatively slow response of the catchment The effectiveness of the ARMA error-predictor is shown to decrease rapidly with increasing lead-time, and is probably negligible for lead-times beyond about 5 hours.

(a) Simulation mode forecasts



(b) Forecasts incorporating error prediction

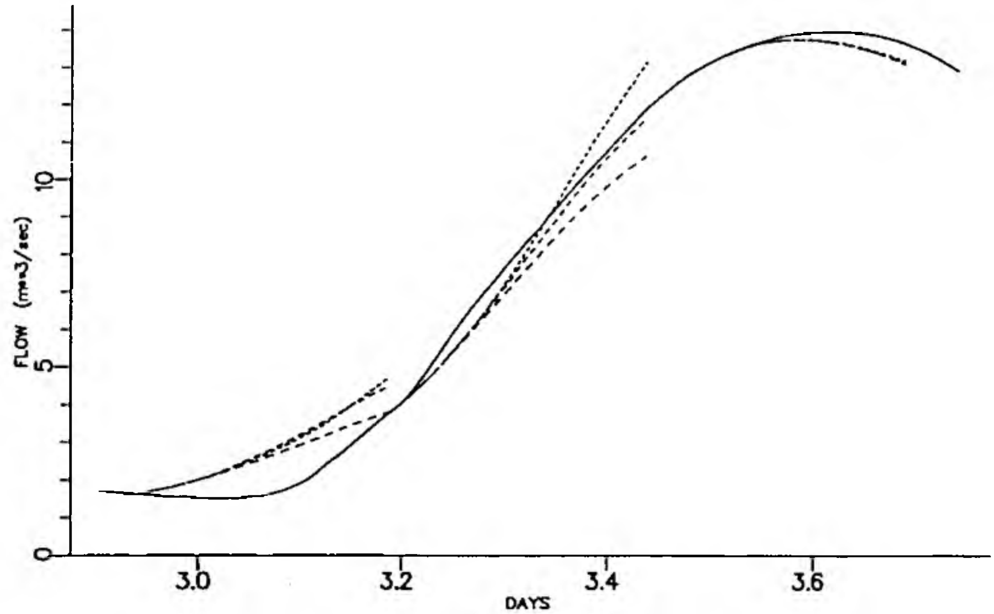


Figure 6.5.2 Fixed-origin forecasts at 16, 10 and 4 hours before the main hydrograph peak for the event of 25-30 October 1990. Thames Conceptual Model of the River Mole at Kinnersley Manor. Forecasts made using observed radar data (short dashes), local radar rainfall forecasts (medium dashes) and Frontiers forecasts (long dashes) as input. Solid lines are used for the observed flow.

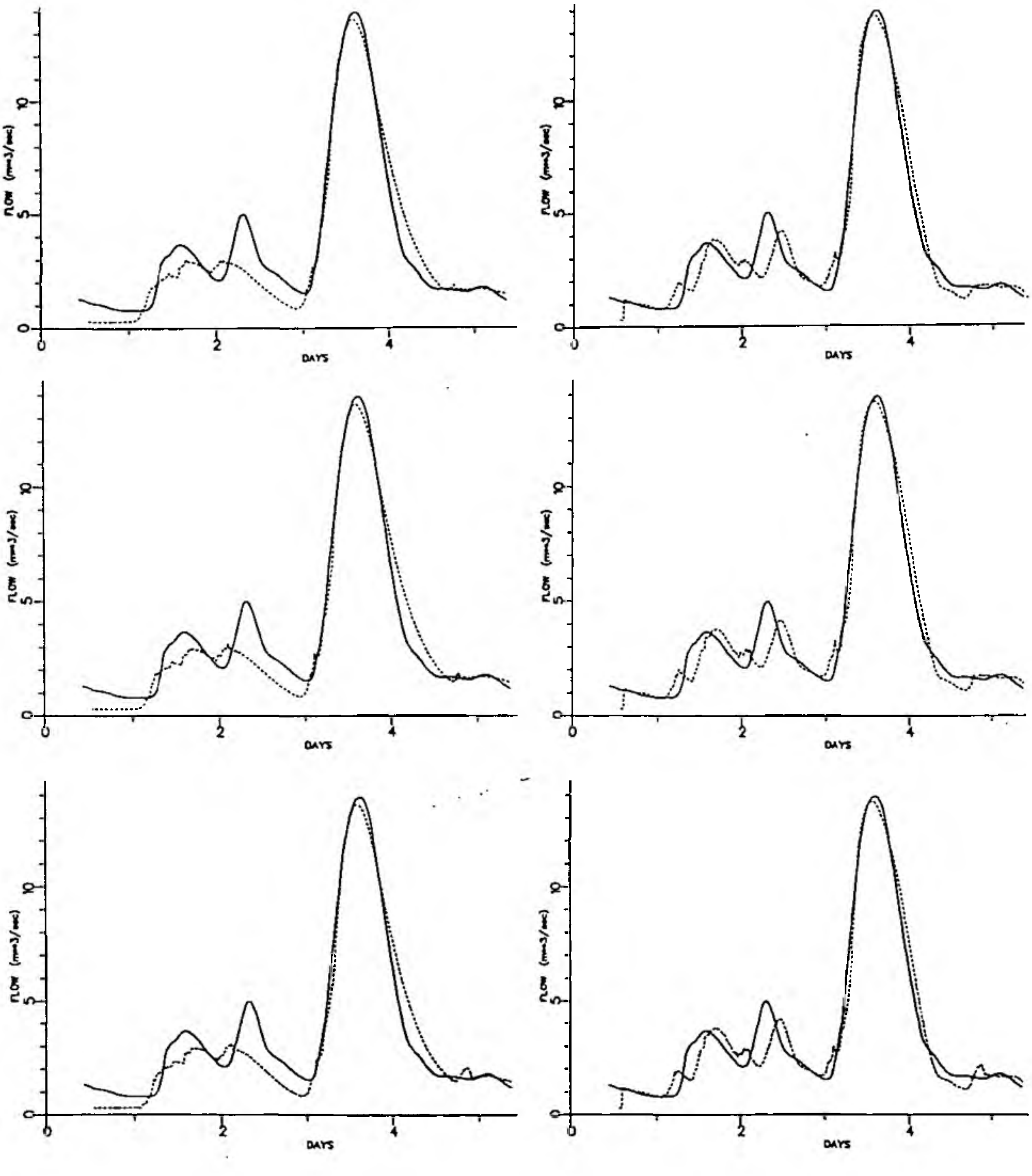


Figure 6.5.3 4-hour fixed lead-time forecasts for the event of 25-30 October 1990. Thames Conceptual Model of the River Mole at Kinnersley Manor. Solid lines are observed flow, dashed lines are forecasts. Results for simulation mode (left) and error-prediction mode (right) using forecast rainfall given by observed radar (top), local forecast (middle) or FRONTIERS forecast (bottom).

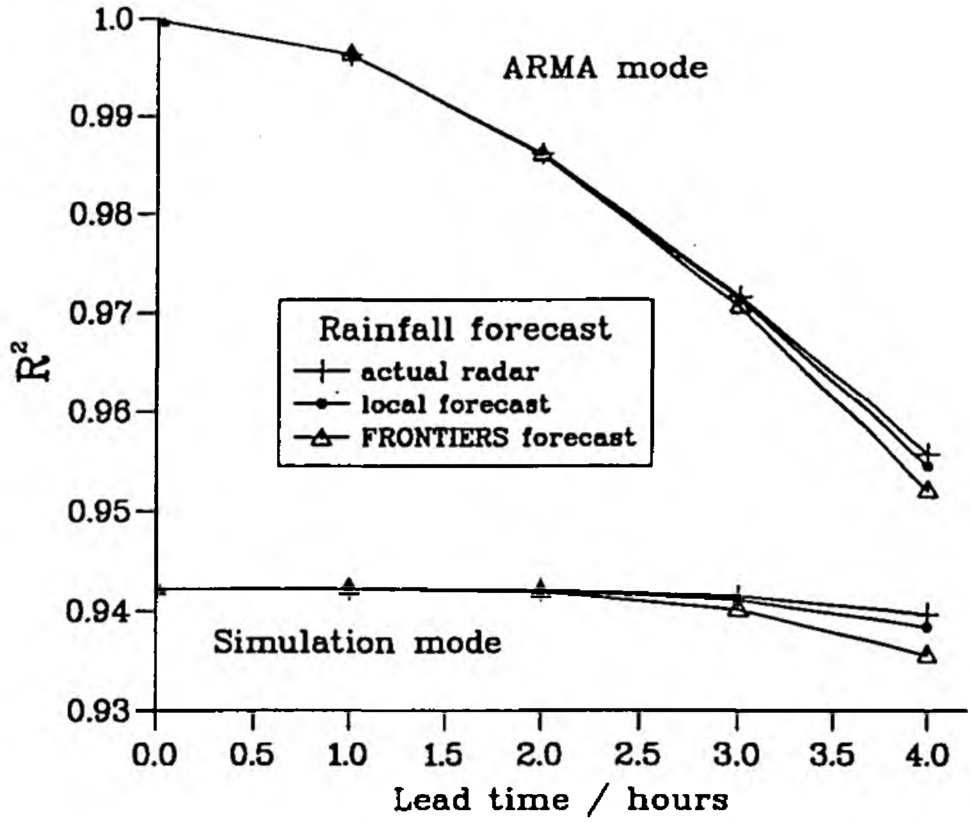


Figure 6.5.4 Forecast performance with increasing lead time for the Thames Conceptual Model of the River Mole at Kinnersley Manor during the event of 25-30 October 1990.

7. SUMMARY AND PLANS FOR FUTURE WORK

The database structure which will support the modelling study is now in place. Software developed for data acquisition correctly handles data formats from all anticipated data sources, and sufficient data has been loaded to allow the model and forecast evaluation process to begin.

The three main types of flood forecasting model - the Thames Conceptual Model, the Isolated Event Model, and the Probability-Distributed Model - have been implemented within the IH model calibration and assessment software environment. Further work will be required to provide raingauge averaging, rainfall zoning, and state-correction for all models. However, the only major task of software development still remaining is the implementation of the Synthetic Unit Hydrograph Model.

Rainfall forecasts derived from the Local Radar Rainfall Forecasting system or from Frontiers can now be deployed within the flood forecasting models, and provision will be made for other forms of rainfall forecast.

The framework for the full-scale evaluation of forecasting methods has been outlined, and a demonstration of the procedure for a simple example has been presented.

The next major phase of the project will be the calibration of models for the eight study catchments using the three types of model presently implemented. As immediate priorities, this will require the completion of the minor software development tasks outlined above, and the loading of further event data presently either held at IH in original source format, or shortly to be acquired from the NRA Thames Region.

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ANNEX A: NON-LINEAR STORAGE MODELS

Non-linear storage models commonly occur as one or more elements in many conceptual models of the rainfall-runoff process. They appear as elements in the Thames Conceptual Model, the Isolated Event Model and in the Probability Distributed Model and thus are reviewed here to provide part of the theoretical background necessary to understand these models.

The outflow from a conceptual model store, $q \equiv q(t)$, is considered to be proportional to some power of the volume of water held in the storage, $S \equiv S(t)$, so that

$$q = k\, S^m, \qquad k>0\ ,\ m>0. \tag{1}$$

The storage, for example, could be a soil column or aquifer storage at the catchment scale. Combining the power equation (1) with the equation of continuity

$$\frac{dS}{dt} = u - q, \tag{2}$$

where $u \equiv u(t)$ is the input to the store (e.g. effective rainfall), gives

$$\frac{dq}{dt} = a(u - q)q^b, \qquad q>0, -\infty<b<1, \tag{3}$$

where $a = mk^{1/m}$ and $b = (m-1)/m$ are two parameters. This ordinary differential equation has become known as the Horton-Izzard model (Dooge, 1973) and can be solved exactly for any rational value of n (Gill, 1976, 1977).

Horton (1945) considered non-linear storage models as descriptors of the overland flow process. Considering turbulent sheet flow from a slope of unit width, Manning-Strickler gives the velocity as

$$v = n^{-1}\, R^{2/3}\ \sqrt{s_o}, \tag{4}$$

where n is Manning's roughness, s_o is the slope, and R is the hydraulic radius which for sheet flow is the depth of water storage, S. Therefore the discharge is given by

$$q = vS = k\, S^{5/3} \tag{5}$$

where $k = \sqrt{s_o}/n$, and consequently the exponent m for fully turbulent flow is $m = 5/3$. For fully laminar flow the exponent of the power relation can be shown to be 3. This allowed Horton to define an "index of turbulence":

$$I = \frac{3}{4}(3 - m) \qquad (6)$$

ranging from I = 1 for turbulent flow (m = 5/3) to I = 0 for laminar flow (m = 3). A solution in terms of tanh (the hyperbolic tangent) is obtained for the Horton-Izzard equation for m = 2 (b = 1/3) in Horton (1938). The exponent m = 2 corresponds to I = .75 and therefore was referred to as the "75% turbulent flow" case. Horton remarked in his 1938 paper about the insensitivity to the value of the exponent m, provided k could be adjusted to compensate; subsequent workers have therefore tended to choose an appropriate value of m and optimised k in some manner to avoid the problem of interdependence between k and m. Horton found that m = 2 was a reasonable choice for overland flow on most naturally occurring surfaces. Although Horton considered overland flow, and S to be the depth of overland flow, it is reasonable to extend the idea to any input-storage-output system, so S could, for example, be the average depth of water stored over a basin, possibly in the form of soil moisture and/or as channel storage. The Horton-Izzard equation may then be regarded as a lumped conceptual model of the rainfall-runoff process at the basin scale.

For m = 1 (b = 0) the Horton-Izzard equation reduces to the linear reservoir model with the recursive solution in terms of q(t) given by

$$q_{t+T} = e^{-Tk}\, q_t + (1 - e^{-Tk})u.$$

This is used in the Thames Conceptual Model to represent unsaturated soil storage.
When m = 2, the resulting storage function, $q = kS^2$, is that for 75% overland flow (Horton, 1945); it is also termed an "unconfined or non-artesian" storage element by Ding (1967) following Werner and Sundquist's (1951) solution for the recession curve (i.e. u = 0) of a deep unconfined aquifer. This storage function was used by Mandeville (1975) as the basis of the Isolated Event Model (IEM) used in the UK Flood Study (NERC, 1975). Here it was developed for deriving design flood hydrographs, in part on account of its efficient parameterisation (the one parameter, k) and sensible response shape offering the prospect of successful regionalisation of the model to obtain design hydrographs for ungauged catchments. Mandeville found that its recession behaviour was too steep for larger, lowland basins, although it performed well on smaller, upland catchments.

To obtain a solution for the Horton-Izzard equation for m = 2, consider first the solution of the general equation for all permissible values of m. Direct integration of (3) for a positive input, u, which is constant in the interval (t, t+T), and noting that

$$\frac{dS}{dt} = \frac{dS}{dq^{1/m}}, \quad \frac{dq^{1/m}}{dt} = \frac{1}{k^{1/m}}, \quad \frac{dq^{1/m}}{dt} = u - q,$$

gives

Making the substitution $v = (q/u)^{1/m}$, and since $dq^{1/m}/dv = u^{1/m}$, then
where $v_1 = (q_{t+T}/u)^{1/m}$, $v_0 = (q_t/u)^{1/m}$; the integral on the left hand side is known as the varied flow function (Chow, 1959). For m = 2 the varied flow function has the analytical solution where c is a constant of integration. Using this result it is readily shown that the solution of (3) for m = 2 is

$$\int_{q_t}^{q_{t+T}} \frac{1}{u-q}\, dq^{1/m} = k^{1/m} \int_t^{t+T} dt,$$

$$\frac{1}{u} \int_{q_t}^{q_{t+T}} \frac{1}{1-q/u}\, dq1/m = k^{1/m}\, T.$$

$$\frac{1}{u} \int_{v_0}^{v_1} \frac{u^{1/m}}{1-v^m}\, dv = k^{1/m}\, T$$

$$\int_{v_0}^{v_1} \frac{1}{1-v^m}\, dv = u^b\, k^{1/m}\, T$$

$$I_2 = \int \frac{1}{1-v^2}\, dv = \tanh^{-1} v + c$$

$$= \frac{1}{2} \log_e \left[\frac{1+v}{1-v} \right] + c, \qquad (7)$$

$$q_{t+T} = u_t \left[\frac{z-1}{1+z} \right]^2 \qquad (8a)$$

$$\text{where } z = \exp(aTu^{1/2}) \left[\frac{1+(q_t/u)^{1/2}}{1-(q_t/u)^{1/2}} \right],$$

or alternatively

$$q_{t+T} = u \left[\frac{(q_t/u)^{1/2} + \tanh\{(uk)^{1/2}T\}}{1 + (q_t/u)^{1/2} \tanh\{(uk)^{1/2}T\}} \right]^2. \qquad (8b)$$

Note that the hyperbolic function relation, tanh (A+B) = (tanh A + tanh B)/(1 + tanh A tanh B), is used in deriving (8b). This predictive equation forms the basis of the Isolated Event Model (NERC, 1975). Whilst originally developed for design application it has been used in modified form for real-time flow forecasting as part of a microprocessor based flood warning system at Haddington in Scotland (Brunsdon and Sargent, 1982); this system continues to be used operationally. The solution provided by equation (8b) is also used in the Thames Water Model to represent release from groundwater storage.

For the recession case when the input, $u = 0$, then the Horton-Izzard equation can be solved for all permissible values of m and k by direct integration as follows:
so
also for the linear reservoirs case ($m = 1$, $b = 0$), then for $u = 0$

$$\int_{q_t}^{q_{t+T}} \frac{1}{q^{b+1}}\, dq = - \int_{t}^{t+T} a\, d\tau$$

$$\left[- \frac{q^{-b}}{b} \right]_{q_t}^{q_{t+T}} = - aT$$

$$q_t^{-b} - q_{t+T}^{-b} = - abT$$

$$q_{t+T} = (q_t^{-b} + abT)^{-1/b} \quad b \neq 0 \ ; \tag{9}$$

$$q_{t+T} = \exp(- kT) q_t \tag{10}$$