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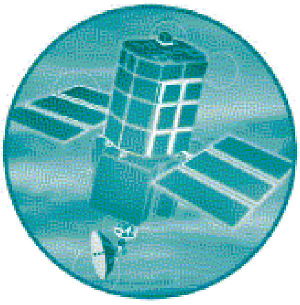

Flood Forecasting – Real Time Modelling

R&D Technical Report W5C-013/5/TR

DEFRA
Department for
Environment,
Food & Rural Affairs

Environment Agency

Flood Forecasting
Real Time Modelling

R&D Technical Report W5C-013/5/TR

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EXECUTIVE SUMMARY

The project 'Flood Forecasting – Rainfall Measurement and Forecasting (WSC13/4) and Real Time Modelling (W5C-013/5/TR)' has two main components:

- Rainfall Measurement and Forecasting techniques
- Real Time Modelling of river levels and flows up to the tidal interface

The project has a number of objectives, the main one being to support an improvement in the quality of operational real time flood forecasting modelling within the Agency, both through preparation of guidelines for use by flood forecasting staff and identification of future priority areas for research and development (improvement plans).

This technical report summarises the outcome of the Real Time Modelling component of the project, and aims to provide both supporting material used in preparation of the separate Guidelines for Real Time Modelling together with a summary of priorities for future Research and Development in Real Time Modelling. The report also describes modelling studies performed during this project into the impacts of uncertainties in rainfall and other input data on the accuracy of flood forecasts.

The main topics considered in this report are:

- existing flood forecasting approaches currently used in England and Wales (the 'current situation'). The approaches reviewed range from simple relationships such as level correlations and time of travel relationships, though to rainfall runoff models, hydrological routing and hydrodynamic routing models. In addition to describing the methods, the assumptions and ease of use of each approach are also identified.

- an overview of forecast uncertainty and a description of the practical approaches that can be adopted to minimise uncertainty in flood forecasts (e.g. model updating), together with a summary of exploratory modelling studies into the magnitudes of some of these effects.

- The main forecasting problems ('issues') identified by Agency staff during a review undertaken at the start of the project

- The technical background to the guidelines on the selection of Real Time Models for fluvial flood forecasting.

- The conclusions from this study on some of the areas where improvements are needed in the form of outline proposals for some 10 potential R&D projects.

GLOSSARY

Term	Description
AVM	Automated Voice Messaging System (automated telephone system for issuing flood warnings)
Baseflow	The stream flow component arising from water moving through the aquifer to the stream channel.
Catchment model	A model (or models) using observations of rainfall and/or upstream flows and/or levels to forecast flows and/or levels at a point within a Flood Warning Area (typically a gauging station)
CNFDR	Changing Needs in Flood Defence Review
Damage avoidance	The potential financial benefit from providing a flood warning taking into account the existing benefits and the costs of property owners acting upon the warning
Flood Estimation Handbook	The standard UK reference for design flood estimation
FHRC	Flood Hazard Research Centre
Flood Risk Area	An area at risk from flooding which may or may not have an existing warning service and is typically based on the Indicative Flood Plain map
Flood Warning Area	An area in which the Agency undertakes to provide a full four stage warning service
Flood Warning Level of Service methodology (FLWOS)	A methodology initially developed by Anglian Region to decide on the appropriate type of warnings to issue in a Flood Warning Area based on the risk and consequences of flooding
Forecasting Point	A location at which it is useful to have a forecast of future levels and flows (e.g. a gauging station, structure, potential flooding location)
Four stage flood warning	• Flood Watch. Flooding possible. Be aware! Be prepared! Watch out! • Flood Warning. Flooding expected affecting homes, businesses and main roads. Act now! • Severe Flood Warning. Severe flooding expected. Imminent danger to life and property. Act now! • All Clear. An all clear will be issued when flood watches or warnings are no longer in force.
Hydrodynamic model	A 1-D, 2-D or 3-D computer solution to the St Venant equations expressing mass and momentum conservation in a river, estuary etc (usually only 1-D for real time river models)
Lead Time	The maximum time ahead which a model or rainfall forecast can predict flows or rainfall
Local Model	A Real Time Model used to provide forecasts at more than one location within a single Flood Warning Area
Locally adjusted radar	Weather radar measurements adjusted in real time using raingauge data for the catchment (see “Guidelines on Rainfall Measurements and Forecasts”)
Nimrod	The Met Office’s current product for delivering rainfall actuals and forecasts for lead times of up to 6 hours ahead (see “Guidelines on Rainfall Measurements and Forecasts”)
PRTF	Physically Realisable Transfer Function; a type of transfer function model in which the parameters are chosen to constrain the estimated flows to be stable and within physically realistic bounds
Potential Accuracy Score	A qualitative estimate of the relative accuracy of a model for solving a given forecasting problem (1,2,3 equates to low, medium, high)
Radar only forecast	A forecast of future rainfall based on advecting (moving) rainfall systems from the current location based on their current speed and direction of motion (see “Guidelines on Rainfall Measurements and Forecasts”)
Rainfall actuals	Observations of rainfall occurring at present using raingauges or radar (see “Guidelines on Rainfall Measurements and Forecasts”)
Rainfall runoff model	A model which converts observed or forecast rainfall into estimated river

	flows at a point
Real time mode (or forecasting mode)	The run time mode for real time models typically including updating and possibly using forecast, rather than observed, rainfall and/or flows (see simulation mode also)
Routing model	A model which translates flows from the upstream to the downstream end of a river reach allowing for floodplain effects, tributary inflows etc
Simulation mode	Typically the mode used to calibrate Real Time Models i.e. using historical data for the full hydrograph without updating (see also real time mode)
Surface runoff	Stream flow that results from precipitation that travels overland (or through shallow soil stores) to the stream channel.
System Environment	The system of computers, software, telemetry, telecommunications etc which supports operation of a Real Time Model
Trigger	A river level above which a flood warning is issued (or considered)
Variable parameter routing	A type of hydrological routing model which allows for variable lag time and attenuation in a river reach through including curves representing the variations of wave speed and attenuation with flow
Ungauged catchment	A catchment with no river level recorder
Updating	The use of observed river levels or flows to attempt to improve a forecast by correcting the forecast to better match the observed values

1. INTRODUCTION

2. BACKGROUND TO PROJECT

The Agency aims to deliver Accurate, Reliable and Timely forecasts of flooding at locations in England and Wales where the benefits justify the costs and where the provision of this service is technically possible. Achieving this aim will contribute to reducing the risks associated with flooding by:

- Supporting the effective delivery of flood warnings to save life, reduce damage to properties and minimise disruptions to communication lines;
- Providing information upon which sound decisions can be made on the operation of river systems and river control structures during flood emergencies.

The Agency states in its Customer Charter (Environment Agency, 2001a) that, regarding warnings;

> *"We will aim to do so at least two hours before flooding happens in areas where a service can be provided.."*

As part of its Flood Warning Service Strategy for England and Wales (Environment Agency, 1999a) the Agency states that it aims to achieve this target by leading work on the best techniques for forecasting and promoting the innovative use of technology that will improve the ability to predict floods.

It is therefore recognised within the Agency that there is clear potential for developing additional or more refined flood forecasting models. However, the particular modelling solutions must be "defensible" and the approach outlined in this report and the related guidelines provides a framework for this. The present project was identified in a portfolio of potential R&D projects by a Concerted Action Workshop which was held in the wake of the Easter 1998 floods (Environment Agency, 2000b) and is being carried out following the damage caused by the Autumn 2000 floods.

For example, in a post-incident report on the Autumn 2000 floods (Environment Agency, 2001c) the Agency concluded that, in Regions where Real Time flood forecasting Models were available, these were mainly used only indicatively to support decisions to issue flood warnings. This reflected a lack of confidence in the model output, in turn attributed to a lack of confidence in weather forecast information and irregular model recalibration and updating (often reflecting a lack of adequate resources). The report also highlighted that, although model runs did in some cases produce accurate estimates of peak flows, the timing and duration of predicted flooding could be inaccurate.

The project has addressed the following four topics:

- Categorising rivers vulnerable to flooding by generic descriptions;
- Categorising modelling approaches and indicating which approach performs better in a given category of physical system;
- Developing cost benefit models;
- Outlining risks associated with particular modelling solutions;

The main outputs from this project are this technical report and a set of "Guidelines for Real Time Modelling" (Environment Agency, 2002b). A related project (WSC013/4) has also produced a separate technical report and guideline document on the subject of "Rainfall Measurements and Forecasts" (Environment Agency, 2002a) covering the availability and use of rainfall information within the Agency for flood warning and forecasting.

2.1 Layout and Contents of Report

This technical report is divided into three main sections:

PART A provides the technical background to the methods presented in the “Real Time Modelling Guidelines” and considers the following topics:

Chapter A.1 summarises national targets for the Accuracy, Reliability and Timeliness of flood warnings and the influence of any available software platforms (i.e. the “System Environment) on model selection; and in particular the implications of the current National Flood Forecasting Modelling System Strategy

Chapter A.2 considers the main forecasting problems (‘issues’) identified by Agency staff during a review at the start of the project

Chapter A.3 reviews the existing Real Time Modelling approaches currently used in England and Wales (the ‘current situation’) and internationally. The approaches reviewed range from simple relationships such as level correlations and time of travel relationships, though to rainfall runoff models, hydrological routing and hydrodynamic routing models.

Chapter A.4 presents the background to the Damage Avoidance Methodology adopted on this project for use in cost-benefit analyses of the viability of proposed Real Time Modelling solutions

Chapter A.5 presents the reasoning behind the Real Time Model selection approaches recommended in the guidelines

PART B then describes the modelling studies and reviews which were performed as part of this project and which have helped to guide the model selection techniques provided in the guideline document.

Chapter B.1 reviews current knowledge on the accuracy of the various categories of Real Time Model described in this report and is based on a review of Agency R&D reports and the international literature. The section also describes statistical and graphical approaches for assessing model uncertainty.

Chapter B.2 describes several case studies of model performance which were performed during this project using operational and other models of the types currently used within the Agency.

Chapter B.3 presents the main conclusions regarding model accuracy and identifies areas of uncertainty which possibly merit future research.

PART C outlines the process by which proposals were developed for potential R&D projects aimed at improving the Agency’s Real Time Modelling capability.

Chapter C.1 presents a brief summary of preliminary conclusions regarding research needs from previous phases of this project, a review of the conclusions from previous Agency projects and from other sources on research priorities in the area of Real Time Modelling, and the final selection of projects for which outline one page summaries appear in Appendix C.

Chapter C.2 presents overall conclusions and recommendations from this project

The appendices provide additional supporting information on the project as follows:

Appendix A presents an amended version of the generic Flood Forecasting Glossary and listing of acronyms/abbreviations produced and maintained by the National Flood Warning Centre. This glossary supplements the report specific glossary provided at the start of this report.

Appendix B	summarises regional flood forecasting issues identified by Agency flood warning staff during a review at the start of this project. The information provided by the Agency has been reproduced verbatim and forms the foundation of the guideline document and the present report.
Appendix C	summarises the priority areas identified for future R&D in the form of outline Form A documents (where a Form A is the format used by the Agency and DEFRA for summarising outline R&D proposals).
Appendix D	presents a series of Factsheets on flood forecasting issues identified within the Agency during the course of this project
Appendix E	presents a series of Factsheets giving examples of Real Time Modelling solutions reviewed during the course of this project.

PART A -TECHNICAL BACKGROUND

Part A of the report reviews the main issues which surround the implementation of a new or improved real time modelling solution for a Flood Warning Area. The topics considered are:

- National Flood Warning Targets (Chapter 1)
- The main Flood Forecasting Problems within the Agency at present (Chapter 2)
- Possible approaches to Real Time Modelling (Chapter 3)
- The Damage Avoidance Methodology used for this project (Chapter 4)
- The model selection approaches used in the remainder of these guidelines (Chapter 5)

This work forms the basis of the recommendations made in the corresponding sections of the guideline document.

1. FLOOD WARNING TARGETS

1.1 Introduction

The Agency aims to provide flood warnings in sufficient time for people to take avoiding action and with a minimal number of false alarms. The Agency has a number of High Level Targets for flood warning which include (Environment Agency, 2000d):

- **Reliability, p_f**: an 80% success rate in provision of flood warnings
- **Residents Available**, **p_i** an 80% success rate in the availability of the public to respond
- **Residents Able**, **p_a**: a 95% success rate in the ability of the public to respond
- **Residents Effective, p_c**: an 85% success rate in the ability of the public to take effective action

The Agency's Customer Charter (Environment Agency, 2001a) additionally mentions a two hour minimum warning time which is often referred to as "Timeliness". There are also targets for the Coverage of the flood warning service (i.e. the number of properties receiving a four stage flood warning service) although this falls outside the scope of this project.

When designing or improving a flood forecasting system, there is obviously a need to understand whether the proposed system will meet these various targets. However, for Real Time Modelling, there is the problem that these definitions mostly relate to the performance of an overall system (including detection, forecasting models, forecaster/human decision processes, dissemination mechanisms, condition of flood defences etc) of which Real Time Modelling is just one part.

It is therefore often not possible to say, during the model selection process, if an individual model can meet these targets, and the following sections consider this issue in some detail, and the extent to which the design can be tailored to meet the relevant target. Also, in some Agency documentation, alternative names are used for some of these targets as indicated in the following table.

Table 1.1. Alternative terminology for Agency targets

Current name (Flood Warning Investment Strategy, 2000/01)	Alternative name in some Agency documentation	Proposed new name (Flood Warning Investment Strategy, 2001/02)
Residents Available		Availability
Residents Able		Ability
Residents Effective		Warning Effectiveness
Reliability	Accuracy, Accuracy of Targeting, Hit Rate	System Effectiveness
Timeliness	Lead Time, Warning Time	System Effectiveness (and implicit in Damage Avoidance estimates)

When considering the performance of Real Time Models, the most relevant targets are the Reliability and Timeliness of the warnings provided (as defined in the Glossary), since the other targets relate primarily to the dissemination of warnings, which falls outside the scope of this project. The issue of model Accuracy is also important although, at present, there are no formal targets for the Accuracy which a flood forecasting system should achieve. However, the phrase "Accuracy, Reliability and Timeliness" (the so-called ART of flood forecasting) appears in many Agency R&D and other reports so it is convenient to consider Accuracy here as another component of overall system performance.

Of these three quantities (Accuracy, Reliability and Timeliness), the Reliability is most easily discussed in combination with the Damage Avoidance estimation technique used on this project, so discussion is deferred until Section 4. Of the remaining two parameters, the easiest to define is Timeliness, followed by Accuracy, so the discussion proceeds in that order:

1.2 Timeliness

Timeliness is defined in terms of the lead time in issuing flood warnings and was described in the Agency's Flood Warning Service Strategy (Environment Agency, 1999a) as:

> *"Prior warning will be provided (two hours in general) to people living in designated flood risk areas where a flood forecasting facility exists and where lead times enable us to do so"*

The latest (2001) version of the Agency's Customer Charter states this slightly differently as:

> *"We will aim to do so at least two hours before flooding happens in areas where a service can be provided"*

i.e. where it is both technically feasible and economically justified.

On a practical level, most Regions aim to offer a lead time for warnings considerably better than two hours where this is technically possible, and Damage Avoidance studies (see later) show that the maximum financial benefits are typically achieved with warnings of four hours or more (although with little additional financial advantage for warnings much beyond 6-8 hours ahead). For example, Table 1.2 indicates some indicative targets first suggested at the 1999 Concerted Action Workshop for Flood Forecasting and Warning for three types of stakeholder (public, emergency services, Agency staff):

Table 1.2. Forecast Timeliness Requirements (Environment Agency, 2000b)

Service level	Public	Emergency services	Agency staff
Warning time (hours)	2	6	6
Accuracy of warning time (+/- hours)	1	3	3

although it was acknowledged that further work is required to refine these targets for different types of flood risk and recipients of warnings (and this recommendation is reinforced later in this report through including this issue as part of a potential R&D topic on review and definition of targets for different types of flood risk and recipients of warnings).

Although not explicitly stated, one interpretation is that this lead time should be based on the minimum warning time given to the properties which are actually flooded in an event. One possible definition of 'timeliness' is therefore that it is the minimum warning time which any single property owner in a Flood Warning Area receives before the onset of flooding at their property (which may not necessarily be the first property flooded). For the guideline document, the following definition of "Timeliness" has been provided by the Project Board:

> *"Timeliness" expresses the expected requirements of the population at risk of flooding in terms of the time needed for effective mitigatory actions.*

However, for these guidelines, the alternative name "Minimum Warning Time" has been adopted in places to illustrate the purpose of this target.

This minimum warning time is, of course, only one aspect of a forecasting process which can include:

- The time taken for the telemetry system to poll all outstations in the catchment
- The time taken to process and quality control incoming data

- The time interval at which Met Office rainfall actuals/forecasts are received
- The time taken for a forecasting model to run and the time interval between each run
- The lead time provided by the forecasting model(s)
- The appropriateness of any trigger levels or alarms which are set including contingencies
- The time taken to run additional 'what if' scenarios and interpret the results
- The time taken for flood warning staff to interpret forecasts and decide whether to issue a warning
- The time taken for warnings to be issued via AVM, flood wardens etc to all properties at risk

Figure 1.1 attempts to illustrate how this measure of timeliness relates to these other time 'delays' for the simplified case of a single isolated storm in a fast response catchment and a model using only rainfall actuals (not forecasts).

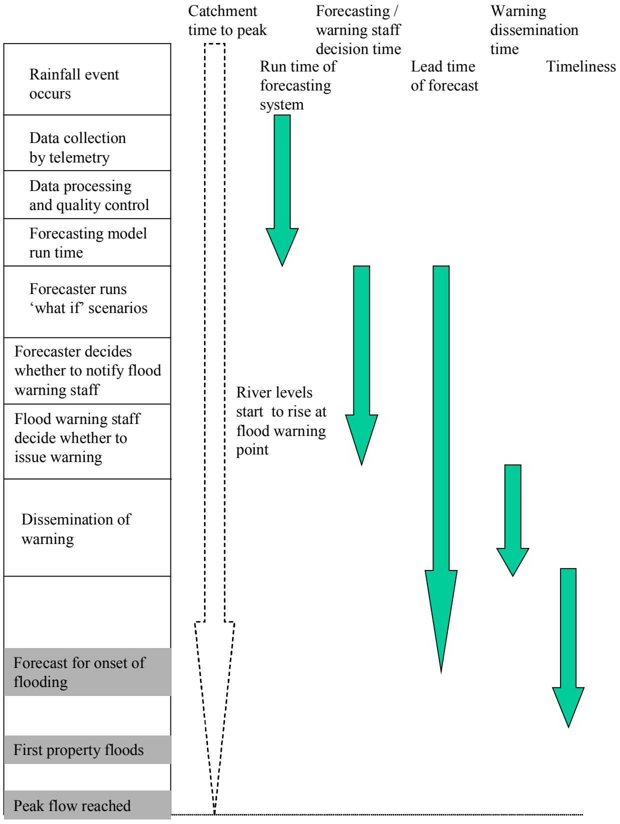


Figure 1.1. Illustrative example of the various time delays in the flood warning process

Clearly, if all other times in the warning process are known, it should be possible to estimate the "timeliness" of a flood warning system at the design stage, and several attempts have been made to do this of which the most well known within the Agency are from the following sources:

a) Reed (1984)

Based on case studies for a few example catchments, Reed proposed the following tentative guidelines for model selection based on catchment time to peak, whilst pointing out that the time to peak is only an approximation to travel times, and several other possible problems with this classification.

- $T_p \leq 3$ hours Use rainfall runoff modelling based on rainfall forecasts (Nimrod/radar-only)
- $3 \leq T_p \leq 9$ hours Use rainfall runoff modelling based on actual rainfall (raingauge/radar)
- $T_p \geq 9$ hours Use flow routing

This approach has often been quoted in Agency documentation, and is used as a simple rule of thumb in the guidelines although the criterion for using routing models is possibly pessimistic, since routing models can in practice be sometimes successfully applied to a location where the time to peak is less than 9 hours. Coincidentally, the current 2 hour minimum warning time target, combined with a typical decision/dissemination time of 1 hour, would lead to the figure of 3 hours or less for use of rainfall forecasts.

b) Environment Agency, 1998c

In this approach, a distinction is made between the catchment time to peak, and the time taken to route flows from an upstream station (strictly the minimum time of travel of a flood wave in the reach). A contingency (time delay) is introduced to allow for the time taken from a trigger level being reached to flooding occurring. The model selection criterion is then:

$T_{route} + T_{contingency} > T_{warnng\ time}$	Use flow routing
$T_p + T_{contingency} > T_{warning\ time} > T_{route} + T_{contingency}$	Use a rainfall runoff model with rainfall actuals
$T_P + T_{contingency} < T_{warning\ time}$	Use a rainfall runoff model with forecast rainfall

This is a slightly simplified (although useful) version of the following method which is used in these guidelines.

c) Present guidelines

The model selection criterion used in these guidelines is based upon that outlined in Environment Agency (1996), with a key improvement being provided by Midlands Region by noting that any such approach should use parameters which are easily measured in operational use (Environment Agency, 1998d).

These methods have been developed further as part of the present project to provide a practical approach which can be used in the guideline document, and the method is illustrated using the example shown in Table 1.3.

Table 1.3. Example of a scenario in which a Flood Warning is issued based on forecast levels

Time	Description	Symbol
12:25	The forecasting model first predicts that levels will rise sufficiently to cause flooding at the Flood Warning Area	T1
12:35	Based on flow/level forecasts, 'what if' model runs, and current rainfall and radar images/forecasts received from the Flood Forecaster, the Flood Warning Duty Officer decides to issue a Flood Warning	T2
12:55	The AVM dial out process is completed	T3
14:45	The Flood Warning trigger level is exceeded at the Forecasting Point	T4
15:10	The first property floods	T5

In this simple example, assuming the worst case scenario that the last property notified was the first to be flooded, then the minimum warning time achieved is clearly $\Delta T_{warning}$ = T5-T3 = 2 hours 15 minutes.

As noted by Midlands Region, the time T2 is typically logged in the AVM database and the time T4 can be obtained from the 15 minute values recorded at the Forecasting Point, whilst all other times must be estimated from local knowledge. For post event analyses, it is therefore useful to derive a relationship between the minimum warning time $\Delta T_{warning}$ and those values which are logged. The relationship between these times is given by:

$$\Delta T_{warning} = (T5-T3) = (T5-T4)+(T4-T3)$$

$$= \Delta T_{local} + (T4-T2)-(T3-T2)$$

$$= (T4-T2) + \Delta T_{local} - \Delta T_{dial}$$

where:

ΔT_{local} = (T5-T4) = the time delay between the trigger level being exceeded and the first property being flooded (effectively the contingency in the trigger)
ΔT_{dial} = (T3-T2) = the time taken to dial out to all properties

and a ΔT symbol indicates a time difference rather than an actual recorded time. Using the example above, ΔT_{dial} = 20 minutes and ΔT_{local} = 25 minutes so that $\Delta T_{warning}$ = 130 + 25 - 20 = 125 minutes = 2 hours 15 minutes as before.

Note that, in some cases, that ΔT_{local} can be large, for example, if warnings are based on an off-site trigger.

For design purposes, it is also useful to relate the time to peak of the catchment to these times so that an estimate can be obtained for the likely minimum warning time of a proposed flood forecasting system. To do this, it is necessary to introduce three new parameters into the analysis:

T0 = the actual time at which the peak rainfall is observed
$\Delta T_{telemetry}$ = the longest likely time taken for the telemetry system to detect the rainfall
ΔT_{model} = the longest likely run time for the forecasting model

The time at which peak levels or flows occurs will usually be at or later than the time at which the first property floods unless local factors have an effect (e.g. debris blocking a bridge) so that T_p exceeds T5-T0 and the time to peak can therefore be written as:

$$Tp \approx (T5\text{-}T0) = \Delta T_{warning} + \Delta T_{telemetry} + \Delta T_{model} + \Delta T_{decision} + \Delta T_{dial}$$

or:

$$\Delta T_{warning} \approx T_p - \Delta T_{telemetry} - \Delta T_{model} - \Delta T_{decision} - \Delta T_{dial}$$

For the Agency's standard 15 minute reporting interval, the detection time $\Delta T_{telemetry}$ is unlikely to be more than 15 minutes and models are typically designed to run within this period. In the above example, the time taken for the forecaster to warn the Duty Officer, and for a warning to be issued, $\Delta T_{decision}$ was 10 minutes although this clearly varies depending on the individual concerned and the other tasks being performed.

Taking, for example, a time to peak T5-T0 of 3 hours, with ΔT_{dial} = 20 minutes, $\Delta T_{decision}$ = 10 minutes, $\Delta T_{telemetry}$ = 15 minutes and ΔT_{model} = 5 minutes, then the best achievable warning time $\Delta T_{warning}$ would be 180-15-5-10-20 minutes, or 2 hours 10 minutes. Alternatively, it could be estimated that, for this example, the target warning time of 2 hours can only be achieved if the time to peak is at least 120+15+5+10+20 = 170 minutes = 2 hours 50 minutes.

If a rainfall forecast is used, the forecast lead time should be added to the time to peak whilst, for cases where forecasts are based on upstream river levels or flows, the time to peak value can be replaced by the minimum likely time of travel of a flood wave from that point to the Forecasting Point.

This analysis leads to the methodology recommended in the guidelines which is that, for estimating "timeliness" at the design stage, users should complete the following table, either supplying their own estimates or accepting the default values suggested.

Table 1.4. Calculation table to support estimates of timeliness at the design stage

Time delay	**Definition**	**Default value (minutes)**	**Locally supplied value (minutes)**
$\Delta T_{telemetry}$	The maximum time taken for information to be received by telemetry	15	
ΔT_{model}	The maximum time taken for a routine real time model run	5	
$\Delta T_{decision}$	The maximum time taken for forecasting and warning staff to act upon a forecast of levels exceeding a Flood Warning trigger level (e.g. whilst performing 'what if' runs)	30	
ΔT_{dial}	The maximum time taken for all properties to be warned e.g. via an automated dialling system	30	
ΔT_{total}	**The sum of the above**	**Site specific**	
Tp	An estimate for the time taken for the maximum flow to be reached at the forecasting point following the peak catchment average rainfall	Site specific	
$\Delta T_{warning}$	The minimum warning time ("Timeliness") likely to be achieved, given by $\Delta T_{warning} \approx Tp - \Delta T_{total}$	Site specific	

whilst, for post event estimates of "timeliness", the following table should be used instead:

Table 1.5. Calculation table to support estimates of timeliness for post event analysis

Time delay	**Definition**	**Default value (minutes)**	**Locally supplied value (minutes)**
ΔT_{dial}	The maximum time taken for all properties to be warned e.g. via AVM	20	
ΔT_{local}	The likely time taken between levels exceeding a Flood Warning trigger level and the first property being flooded	Site specific	
T4-T2	The time difference between issuing a warning and the Flood Warning trigger level being exceeded at the forecasting point	Site specific	
$\Delta T_{warning}$	The minimum warning time ("Timeliness") actually achieved in an event, given by $\Delta T_{warning} \approx (T4-T2) + \Delta T_{local} - \Delta T_{dial}$	Site specific	

Values for the time to peak can be estimated from rainfall and river level/flow data, from the Flood Estimation Handbook catchment descriptors, or from previously developed models and reports (e.g. Section 105 reports). For the case that forecasts are derived from observed river levels or flows at an upstream station (or stations), then the time to peak should be replaced by the minimum likely travel time to the forecasting point from the uppermost station used in the procedure. If rainfall forecasts are used in addition to rainfall measurements, then the lead time for the rainfall forecasts should be added to the time to peak.

1.3 Accuracy

Whilst the Agency's definitions of Timeliness and Reliability are reasonably clear-cut, those for Accuracy are less so. This point was acknowledged at the Concerted Action Workshop (see previous section) which suggested the following tentative definitions and estimates:

Table 1.6. Forecast Accuracy Requirements (Environment Agency, 2000b)

Service level	Public	Emergency services	Agency staff
Accuracy of flood depth forecast (+/- metres)	0.5	1	2
Accuracy of flood duration estimate (+/- hours)	3	3	3
Accuracy of targeting (%)	80	100	N/A
Reliability (%)	75	50	50

Here, the 'accuracy of targeting' relates to predicting the locations at which flooding will occur, whereas the 'Reliability' under the 'Public' column is the same term as that defined later (Section 4). Regarding the accuracy of flood duration, it is not stated whether this is the duration at the first property flooded, the last property flooded, or measured by when the river goes out of bank (or over the flood defence) at the forecast point.

Regarding a definition for accuracy, the following definition has been provided for use on this project by the Project Board:

"Accuracy" *expresses the expected technical performance of a flood forecasting and warning system expressed in terms of appropriate criteria at interfaces (e.g. peak level reached, depth and extent of flooding etc at the interface between flood forecasting and flood warning)*

Table 1.6, although a useful starting point, could clearly be developed further to allow for the fact that the required level of service will often vary according to:

- The nature of the flooding problem
- The consequences of flooding
- The nature of the information required by the public or emergency services
- The size/depth of the river at the forecasting point

Flooding typically occurs either due to an unprotected river going out of bank, or flood defences being overtopped or breached. The timing and location of breaching of defences cannot usually be predicted by a flood forecasting model (unless it is known that, at a certain level, a defence will fail due to its weakened condition) and will not be considered here. For flood defences, a typical 'design' freeboard would be in the range 0.2-0.5 metres and so the accuracy required on peak levels might be in this range (although not necessarily achievable depending on the complexity of the flooding problem and the choice of model). For undefended reaches, a lower accuracy might be required, and even a simple 'flood/not flood' prediction might be of use, with the ultimate level reached, and its timing, being of secondary importance. On rivers with flow diversion structures or reservoirs, the advance warning required to take meaningful action will typically be site specific, and can be several hours in some cases. In such cases, the accuracy and reliability requirements will also be site specific; for example, to support the use of washlands etc.

The consequences of flooding also vary, and can impact on the level of service required of any flood warning system. For defended reaches, if flooding occurs, the consequences can often be severe, due to the large depths reached, high population densities and the resulting high risk to life or damage to property. The consequences of providing false alarms can also be serious; for example, evacuations pose a risk to some groups, such as the elderly and hospital patients. There can therefore be stringent requirements on reliability and on the timing of the onset of flooding. In lower risk situations (e.g. flooding of agricultural land), a simple yes/no prediction may be sufficient, although there is of course a whole range of situations between these extremes.

The level of service required may also be guided by the nature of the information required by the public and emergency services (and Agency staff) and the likely precision demanded by these ‘customers’. Table 1.7 shows some typical ‘questions’ asked during a flood event and indicates how these might translate into accuracy requirements (an extended version of this list appears in the guidelines).

Many of these requirements relate to the crossing of threshold levels such as the top of flood defences or trigger levels, and this topic is discussed further later. Clearly, further research is needed in the area of the requirements for Accuracy and this is one of the R&D topics identified in Part C of this report.

Table 1.7. Typical information requirements of the public, emergency services etc

Question	Typical Requirements
When will the flooding begin?	Time at which a threshold level is reached
What depths will be reached?	The peak level reached and/or the volume of water spilling onto the floodplain
How long will the flooding last?	Times of crossing a threshold (rising and falling limb)
When can the ‘all clear’ be issued?	Time of dropping below a threshold
Which properties will be flooded?	Volume of flood over a threshold and location of any overtopping
Will this road/railway be flooded?	Location of flooding along the reach and timing/depths/velocities
Should temporary gates be raised/lowered?	Usually based on one or more predicted trigger levels
Should flow control structures be operated?	Time of onset of flooding (maybe several hours warning)

1.4 System Environment

The System Environment is the network of computers, telemetry systems, databases, software etc which support Real Time Modelling. The availability (or otherwise) of a suitable system can have a strong impact on the performance (e.g. “Timeliness”) and the technical and economic feasibility of any proposed Real Time Modelling solution for flood forecasting; for example, although a real time hydrodynamic model may be the optimum technical solution, there are cost and time implications if a run time environment needs to be developed from scratch, and staff trained in its use.

Similarly, a review of Regional flood forecasting capability may suggest implementation of a large number of simpler ‘stand-alone’ models which it would not be practicable to run simultaneously in real time during a major widespread flood event without the automated run control provided by a well designed system. Also, any existing system may only support calibration and real time operation of a limited selection of models.

These issues have long been recognised and most Regions have some form of region-wide forecasting system. Most recently (2002), Anglian Region have commissioned a new modelling and display system (the Anglian Flow Forecasting Modelling System) and new flood forecasting systems will be commissioned in Southern, North East and Midlands regions starting from 2003.

The basic concept of these new systems is of an ‘open shell’ which can host any model which corresponds to the specification provided. Issues handled by the ‘shell’ include:

- Computer and communications infrastructure
- The modelling shell or framework
- Models – rainfall runoff, routing etc
- Real time updating

- User interface
- Data storage and maintenance
- Audit trail
- Interfaces with other systems

In a typical installation, any existing models will be implemented within the new system, possibly with some additional pilot studies to demonstrate the use of more advanced modelling approaches.

Additional benefits may also arise from other types of real time modelling e.g. pollution modelling, low flow forecasting etc although these issues are not discussed in this report.

Regarding 'what if' analyses, most modern systems also allow the user to assess the sensitivity of forecasts to the input data; for example, using:

- Raingauge data only
- Radar-only
- User defined rainfall scenarios (e.g. no future rain, rainfall continues as now, winter rainfall profile)
- Locally adjusted radar
- Nimrod forecasts
- River control gate settings

Manual intervention may also be possible to change parameters such as the depth of snow cover, reservoir or washland gate settings and levels, assumptions regarding ungauged tributary inflows etc.

The model calibration environment is also another aspect of the system environment, with the best available models currently providing:

- A choice of optimisation criteria and algorithms
- Graphical and statistical displays of model performance
- Options to evaluate model performance in simulation and real time modes
- Joint calibration of the model and updating routines

The following table summarises the main System Environment issues for various categories of Real Time Model. Here, a 'shell' is taken to be any software system which – as a minimum - handles the capture of data from the telemetry system or a database and automatic running of models. Facilities to plot and print results are also common features.

Table 1.8. System environment issues for real time models

Model type	Calibration	Real time use
Correlation models	A calculator or spreadsheet is sufficient for single correlations, with a specialist package advisable for multiple correlations	Simple enough to use manually, or to programme into the telemetry system (not all systems) or to use in a full 'shell'
Transfer function models	Ideally requires a specialist statistical package to decide the appropriate structure and parameters of the model but could be programmed in a spreadsheet	Some versions simple enough to use in a spreadsheet although a 'shell' is required to take full advantage of updating, non linear versions etc
Conceptual models	Requires a specialist package to decide the appropriate parameters of the model (and structure, where more than one configuration is possible)	Requires a 'shell' type environment
Routing models	Fixed parameter versions could be calibrated by calculator or spreadsheet but a specialist package is generally advisable, and essential with variable parameters and when the reach is divided into subreaches	Normally requires a 'shell' type environment
Hydrodynamic models	Specialist package essential	Requires a 'shell' type environment
Updating methods	Error prediction methods require a statistical fitting package (usually part of the overall model) and state and parameter updating techniques are entirely model dependent so will form part of the overall model calibration environment	Requires a 'shell' type environment to calculate and display the results

2. FLOOD FORECASTING PROBLEMS IN THE AGENCY

2.1 Introduction

Consultations as part of this project (see Appendix B) suggested that the main catchment related flood forecasting issues within the Agency at present are (Table 2.1):

- Fast Response Catchments
- Confluence Flooding
- Influence of Structures
- Floodplain Storage
- Low Benefit Locations
- Influence of Groundwater
- Urban Catchments
- Reservoired Catchments
- Complex Channels/Catchments

Some other issues identified included data availability (discussed in the guidelines), flows downstream of the Fluvial/Tidal boundary (outside the scope of these guidelines; see Environment Agency, 2001b), and snowmelt and ice-formation problems (which were not thought to be of high priority by Agency Flood Warning staff, although snowmelt issues are discussed later).

Table 2.1. Summary of Fluvial Flood Forecasting Problems in the Agency

Forecasting Problem	Main Issue	Typical best practice solution
Fast Response Catchments	Short warning times	Rainfall runoff models using raingauge or radar measurements and (possibly) radar-based forecasts e.g. Nimrod, locally adjusted
Confluence Flooding	Backwater influences Ungauged inflows	Ideally hydrodynamic models but also summation of flows, multiple correlations
Influence of Structures	Backwater effects Impact on flows downstream	Maybe hydrodynamic models near the structure. Routing, correlation etc downstream
Floodplain Storage	Modified flows and volumes throughout the event	Variable parameter routing methods, correlations or hydrodynamic models
Low Benefit Locations	Cost benefit analyses place limits on what can be justified	Correlation, simple rainfall runoff models or Flood Watch contingency tables
Influence of Groundwater	Long duration events in unanticipated locations	Rainfall runoff, correlation models, maybe aquifer models
Urban Catchments	Short warning times and influence of structures	Rainfall runoff, hydrodynamic and urban drainage models (however urban drainage problems at pumping stations, sewerage systems etc are outside the Agency's responsibility and often require complex hydraulic models)
Reservoired Catchments	Artificial influence on flows and possible flood storage (although often outside the control of the Agency)	Water balance, routing, hydrodynamic, correlation with the need to model control rules and releases if the reservoir is not spilling
Complex Channels/Catchments	Flood relief or natural channels	Hydrodynamic models, multiple correlations

Appendix D presents a series of Factsheets on these topics whilst the following descriptions give more details on the issues which were raised.

Table 2.2. Factsheets for Examples of Agency Flood Forecasting Issues

Method	Factsheet	Region	River/location
Fast Response Catchments	FF1	North East	Upper Calder
	FF2	South West	Sid
	FF3	Wales	Afon Clun
Confluence Flooding	FF4	Southern	Yalding
	FF5	North East	Ure
	FF6	Thames	Loddon
Influence of Structures	FF7	North East	Don
Low Benefit Locations	FF8	Anglian	East Suffolk rivers
		Wales	Teifi
		Midlands	Leam
Floodplain Storage	FF9	North East	Tees
Influence of Groundwater	FF10	South West	Avon
	FF11	Anglian	Slea
Urban Catchments	FF12	Thames	Ravensbourne
		Midlands	Tame
Reservoired catchments	FF13	Wales	Afon Rheidol
	FF14	Anglian	Eyebrook
Complex channels/catchments	FF15	South West	Tone
	FF16	Thames	Thames
	FF17	Thames	Lower River Colne

2.2 Fast response catchments

The most common problem (identified by six of the seven responding regions) is forecasting for fast response catchments. For catchments that respond rapidly to rainfall this makes meeting the Timeliness target difficult because times to peak are short, therefore a rainfall runoff based approach is required to provide a sufficient lead-time for flood warning, possibly using rainfall forecasts as well to further extend forecast lead times. Even on large, slow response rivers, rainfall runoff submodels may sometimes be required to estimate flows from fast response tributaries where these make a significant contribution to flood flows. Fast response flooding problems may also arise on non Main River (ordinary/critical ordinary) watercourses.

Following the Easter 1998 floods, the ‘Bye Report’ (Environment Agency, 1998b) identified that a major factor which affected the ability to give timely warnings was the exceptionally rapid rate of rise of the rivers, due to the fast response of catchments caused by the combination of saturated ground and heavy rainfall following above average rainfall in the month leading up to the event. The unusually high and fast response surface runoff rates were not forecast accurately in any of the four Regions studied in that report.

Similar conclusions were reached in the “lessons learned” report on the Autumn 2000 floods (Environment Agency, 2001c) which showed that the extended period of flooding was due to the cumulative effect of a series of “waves” of rainfall, which crossed the country over a seven week period. Catchments soon became waterlogged, with the result that rivers responded rapidly even to modest rainfall and threatened or caused flooding. Groundwater flooding also developed over a period of weeks in several locations (e.g. the city of Chichester, and parts of Yorkshire).

2.3 Confluence Flooding

Forecasting flood levels at or near confluences was identified as a significant problem by six Regions. Confluences are problematic because all the tributary flows need to be considered to provide estimates of flood levels for at risk locations. If a site is located upstream of a confluence then backwater effects also need to be taken into account. Simple hydrologic routing is unable to simulate these backwater effects and therefore ideally hydrodynamic modelling is required although a simple alternative is to use peak flow or level data (if available) to develop a relationship between levels upstream and downstream of the confluence. Current forecasting methods used by the Agency include simple techniques such as summation of flows, rainfall runoff modelling, and hydrodynamic modelling

2.4 Influence of Structures

Structures can include barrages, gated weirs, sluice gates and various other artificial influences on flows e.g. pumps. River levels may be strongly affected in the reaches immediately upstream and downstream of the structure, and there may be an impact on levels and flows at Flood Warning Areas further downstream. Forecasting techniques currently vary according to the expected impact of the structure on flows, and can range from simple correlation methods, rainfall runoff models and routing models to more complex approaches; for example a combined rainfall runoff, kinematic wave and hydrodynamic model is used for the River Tees in the North East Region. The blockage of structures such as culvert debris screens provides an additional complication which is usually tackled by monitoring; for example, using differential head sensors, CCTV cameras or webcams to provide early warning and to facilitate the mobilisation of operations staff.

2.5 Floodplain Storage

Floodplain storage is an important issue for flood forecasting due to its influence on the attenuation and travel time of flood waves and the impact that significant storage can have for the accuracy of downstream forecasts. Many of the simpler modelling techniques (e.g. correlations, routing models with fixed parameters) cannot adequately capture these effects since there is no representation of floodplain storage or flows in the models. Ideally, hydrodynamic routing models or simpler models allowing variable wave speeds etc would be used in this situation. However, when combined with data from real time floodplain level gauges, simple empirical and flow routing models can sometimes be used instead.

2.6 Low Benefit Locations

Low benefit locations are catchments where the benefits from providing a forecast cannot justify the expense of a sophisticated forecasting model. These may include both gauged and ungauged catchments. Typical examples are low risk agricultural land which may be flooded every year, or areas with only a few isolated properties. Cost benefit and risk to life assessments can guide the appropriate flood warning approach; for example, issue of a general Flood Watch, or incorporating these areas into the full four stage warning service for a nearby Flood Warning Area.

2.7 Groundwater Flooding

Groundwater flooding has been identified as being a major issue in several Regions. This type of flooding is slow compared to surface runoff events, but is often of a much longer duration and the associated damage costs can therefore be higher. These events can be hard to predict without recourse to complex numerical modelling due to the complexity of regional groundwater flow and its influence on surface water floods and real time monitoring of groundwater levels is ideally required.

2.8 Urban Catchments

Urban catchments are characterised by high runoff rates and a fast response to rainfall, often over small catchments with areas of a few square kilometres. It is also difficult to predict the timing and magnitude of surface drainage and flows may be affected by structures and flood defence schemes. However, these areas are critical since they are densely populated and therefore flood warning schemes tend to have the highest benefit-cost ratios. It should be noted, however, that to forecast flooding arising from surcharging of the urban drainage system would require a hydrodynamic model of the drainage network.

2.9 Reservoired Catchments

For risk areas which have reservoirs upstream, the storage and operation procedures of these reservoirs can make the forecasting of the timing and magnitude of peak flows difficult. Similar considerations also apply to natural lakes. Outflows can be either measured directly, or predicted using rainfall runoff models to forecast inflows combined with relationships or control rules relating levels to outflows. In the latter case, an overall water balance model is required to determine the level in the reservoir relative to inflow and outflow and, in some cases (e.g. for large reservoirs), the model may require estimates or measurements for the direct rainfall and evaporation at the reservoir surface where these make a significant contribution to the water balance.

2.10 Flooding due to Snowmelt

Snowmelt has the potential to cause significant flooding although the consultations did not show this to be a major forecasting issue in any Region. However, snowmelt models are used operationally in several Regions (e.g. Midlands, Anglian, North East) combined with techniques which aim to estimate the extent and depth of snow cover (e.g. heated raingauges, snow pillows, snow depth observers). Although snowmelt was not a major factor in the recent 1998 and 2000 events, it has been in the past. For example, it contributed to severe flooding in many parts of England and Wales in 1947, and to flooding in the northeast in 1963 and 1982 (and heavy rainfall falling on snowpack can pose a particular risk).

2.11 Complex Channels/Catchments

Complex channel networks may contain structures, flood relief channels, multiple branches to the channel or a combination of these. These aspects can have significant hydraulic influence on flood flows and levels and hence are hard to forecast using simplified or 'lumped' approaches, usually requiring hydrodynamic models.

Table 2.3 provides several examples of Real Time Modelling solutions for some of these problems within the Agency Regions and additional examples appear in the Factsheets in Appendix D and E:

Table 2.3. Example Applications of Real Time Models

Problem	Location	Model Used	Description
Fast Response Catchments	River Irwell (North West)	Flow to flow correlation (supplying approximately 2 hours lead time)	Three tributary gauges measure flow on the major upstream tributaries, and the combination of the flow from these three catchments can be used to predict flow at the downstream location. Success based upon location and availability of upstream flow data.
	North East, Midlands Region	Conceptual rainfall runoff models integrated into the Regional forecasting system	Models using raingauge and/or radar data, and Nimrod forecasts, to estimate inflows into routing models for lower reaches of the catchments
	Upper Ouse (Anglian)	Look up tables derived from HEC-HMS model	Look up tables extend forecast lead time by allowing forecasts to be based on rainfall and SMD data, rather than trigger levels.
Confluence flooding	River Eden (North West)	Combined routing and hydrodynamic model	The model provides six hours or more warning of flooding in Carlisle and improves estimates for the influence of two tributaries within the town on forecast levels compared to the previous multiple correlation approach
Influence of Structures	River Witham (Anglian)	Combined rainfall runoff and Hydrodynamic model	Accurate and explicit representation of hydraulics at all structures (weirs, culverts, dynamic sluices, washland doors and tidal doors).

Floodplain Storage	River Tees (North East)	Rainfall runoff models feeding into variable parameter kinematic wave models of the middle catchment and into a hydrodynamic model of the lower catchment	Good representation of runoff process in upper catchment, routing processes through the simple middle reaches and explicit representation of floodplain dynamics in the lower catchment.
Low Benefit Locations	Midlands, North West	Correlation models	Large numbers of correlations implemented within the telemetry system (North West) and as a back up to the regional forecasting system (Midlands) provide a cheap, robust method for obtaining approximate forecasts throughout much of the river network
Groundwater Flooding	River Slea (Anglian)	Regression between groundwater level and flow plus a rainfall runoff model for surface runoff modelling when groundwater reservoir is saturated.	Strong springflow dominated catchment, with a very good relationship between groundwater level and surface flow. Rainfall runoff modelling ensures that surface runoff peaks are also forecast correctly.
Urban catchments	Thames	Conceptual models using rainfall forecasts	Good progress from R&D over many years on both the meteorological aspects (forecasting convective storms) and use of semi distributed and fully distributed conceptual models in combined rural/urban catchments
Reservoired Catchments	Eyebrook Reservoir (Anglian)	Rainfall runoff model feeds into an explicit 1-D hydrodynamic model representation of the reservoir and its outflow	Rainfall runoff model inflow accurately calibrated to observed reservoir levels (assuming observed outflow); Stage-storage relationship available for reservoir; Reservoir operation modelled explicitly in the 1-D model generating a modelled level and a downstream flow forecast.
Flooding due to snowmelt	North East, Midlands	Conceptual and empirical models	Conceptual models using observed snowdepth data (observers, snow pillows) and air temperature have had some success in predicting excess flows arising from snowmelt (due to suitable monitoring networks in the catchments concerned)
Complex Channels / Catchments	Great Ouse (Anglian)	Threshold Exceedence Tables	Large, predictable catchment, with long travel times, ensures that a simple lookup table of threshold exceedence values provides sufficient forecasting for much of the catchment.

3. APPROACHES TO REAL TIME MODELLING

3.1 Introduction

To discuss modelling approaches, it is convenient to introduce a general categorisation scheme for the main types of models used within the Agency and elsewhere. This provides a way of comparing models enabling general conclusions to be drawn independently of the specific model 'brand' under consideration.

During early stages of this project, feedback from the Project Board was that the following categorisation scheme would be most useful to Agency requirements.

Table 3.1. Model categorisation scheme used on this project

Model type	Example	General categorisation
Rule of Thumb	25 mm of rain in 6 hours on a saturated catchment will cause flooding	Simple empirical methods
Heuristic Rules	Warnings based on river levels at or near to the site (i.e. triggers)	
Empirical Models	Level-level correlation, Floodwatch	
Blackbox models	Transfer function	Rainfall runoff Models
Conceptual models	Conceptual rainfall runoff models	
Hydrological routing	Muskingum routing models	Routing models
Kinematic routing		
Hydrodynamic routing		
Turbulence modelling	Not used in real time at present	
Large Eddy Simulation	Not used in real time at present	

This scheme is based on a combination of data requirements, laws of conservation (mass, momentum etc), spatial resolution and physical layout. Of these approaches, the first two ("Rule of Thumb" and "Heuristic Rules") are not modelling techniques and so are not discussed in the guidelines, whilst the last two approaches ("Turbulence Modelling" and "Large Eddy Simulation") are not used operationally at present (although might become more widespread in future for detailed modelling of the influence of structures and other local effects). The guidelines therefore only cover the highlighted items in the table.

The aim of this section is to outline some of the general principles of Real Time Modelling whilst the following sections (Sections 3.2 to 3.6) describe in more detail some of the main model application issues for the model types listed in Table 3.1 including:

- Data requirements
- Suitability for real time use
- Assumptions and uncertainties
- Suitability for extreme events
- Ease of use – calibration
- Ease of use – operational

Updating routines and approaches to model calibration and recalibration are also discussed. Appendix E also includes a series of Fact Sheets on successful applications of some of these approaches within the Agency Regions and elsewhere (Table 3.2).

Table 3.2. Factsheets for Real Time Modelling approaches

Method	Factsheet	Location
Empirical Methods		
Level-Level correlations	RTM1	River Caldew (North West)
Flow-Flow correlations	RTM2	River Irwell (North West)
Time of Travel Maps	RTM3	River Uck (Southern)
Antecedent Precipitation Index	RTM4	General example from the USA
Flood Watch Thresholds Threshold Exceedence tables	RTM5 RTM6	Thames and Midlands Regions Great Ouse (Anglian)
Black Box Models		
Unit Hydrograph	RTM7	Red River of the North – North Dakota, USA
Transfer Function (PRTF)	RTM8	River Greta (North West)
Transfer Function (PRTF)	RTM9	River Tone (South West)
Artificial Neural Network	RTM10	South River Tyne (North East)
Conceptual Models		
Rainfall Runoff	RTM11	General example
Snowmelt Models	RTM12	North East, Anglian and Midlands
Routing Models		
Hydrological Routing	RTM13	Midlands Region
Hydrodynamic Models		
1D hydrodynamic model	RTM14	River Eden (North West)
1D hydrodynamic model	RTM15	Rivers Welland and Glen (Anglian)

Table 3.3 gives an indication of the types of models which are currently used in the Agency Regions and their main characteristics are briefly outlined in the following sections.

In general, river flows may be forecast either directly at one or more Forecasting Points within a Flood Warning Area, or used as input to additional reservoir or routing models which translate flows to a Forecasting Point further downstream. Predicted flows can be converted to the river levels required for triggering flood warnings if an appropriate rating equation is available for the Forecasting Point, or alternatively used as input to real time local models for the river in and around the Flood Warning Area.

When using rating curves, a common situation which arises under flood flow conditions is that some extrapolation is required beyond the peak measured discharge. Extrapolations of this type can sometimes be performed with confidence when there are no sudden changes in channel cross section at the higher flows, but normally the rating curve should be extended off-line using techniques such as hydrodynamic modelling, velocity-area methods etc. More generally, the suitability of a model when operated under extreme flows is a key factor to consider in model selection; for example, there can be a high risk of poor results in using purely data based methods such as correlations outside their range of calibration.

Table 3.3. Examples of the Real Time Model types used within the Agency Regions

Method	Anglian	Midlands	North East	North West	Southern	South West	Thames	Wales
Empirical methods								
Level-Level correlations	■	■	■	■	■	■	■	■
Flow-Flow correlations				■				
Time of Travel Maps					■			
Antecedent Precipitation								
Flood Watch Thresholds		■				■	■	
Threshold Exceedance	■							
Blackbox models								
Unit Hydrograph								■
Linear TF	■			■	■			
Non linear TF					■			
PRTF				■	■	■		
Artificial Neural Network			□	□				
Conceptual Models								
Rainfall runoff models	■	■	■				■	
Non linear storage models					■			
Snowmelt models	■	■	■					
Routing models								
Muskingum								
Modified Muskingum		■						
Muskingum Cunge								
Kinematic Wave			■				■	
VPMC				■				
1-D hydrodynamic	■		■	■			■	
Updating methods								
Error correction		■	■					
State updating	■		■					
Parameter updating				■		■		■

■	Used operationally
□	Research only at present

Table 3.4. Examples of Real Time Models under evaluation or development

Model type	Potential advantages	Current status
Artificial neural network models	Alternative approach to both rainfall runoff and routing problems using a type of pattern recognition	Recent trial studies in North East Region (see Factsheet RTM10)
Fully distributed rainfall runoff models	Making better use of high resolution weather radar data and forecasts to more accurately model spatial variations in runoff across a catchment	Evaluated as part of R&D 242 (Environment Agency, 2000c) for example
Non linear and parallel pathway transfer function models	Better representation of baseflow and soil moisture impacts on rainfall-runoff processes	Not a new technique but remains an active area of research
Two dimensional hydrodynamic models	Better representation of floodplain depths and flows	Used off-line for many years but real time applications still at the research and evaluation stage e.g. project WSC12 “Real time out of bank inundation models”

3.2 Empirical Models

Empirical methods provide a simple yet robust approach for flood forecasting and are widely used within the Agency either in their own right or as a backup to more sophisticated approaches. The key disadvantage to note is that these methods generally only provide information on part of the hydrograph at the forecasting point; for example, the peak value or the time of arrival of the event. The main techniques used include:

- Level Correlations
- Flow Correlations
- Time of travel estimates
- Antecedent Precipitation Index method
- Flood Watch tables

3.2.1 Level Correlations

Level correlations are widely used throughout England and Wales. Most correlate peak levels at a single downstream forecasting site with peak levels at an upstream station, although there are also several examples of levels at two or more upstream stations being used to forecast level downstream.

3.2.2 Flow Correlations

Flow-flow correlations are also used in several Regions, and the approach taken is the same as with levels. However, the use of a rating equation to convert forecast flows to levels at the Flood Warning Area provides a potential source of error, counterbalanced by the benefits from using a quantity which is conserved. Again, multiple correlations may be used – for example relating flows at the Flood Warning Area to flows on two or more tributaries - and correlations allowing for different types of flood event and rainfall distribution e.g. storms in upper part of catchment, heavy rainfall with snow thaw throughout the catchment, rainfall in summer conditions (drier catchment) etc.

3.2.3 Time of Travel Maps

Time of travel information is usually implicit in correlation based approaches i.e. the correlation relates levels or flows at one point to levels or flows further downstream at a later time. However, time of travel maps can also be used as an additional source of information when forecasting flooding.

3.2.4 Antecedent Precipitation Index/Flood Watch tables

Simple methods are also used in England and Wales to trigger ‘Flood Watch’ conditions and, in some cases, Flood Warnings. Typically, simple thresholding approaches are used incorporating relationships between soil moisture deficit (SMD) and rainfall event depth and duration. These are generally in the form of simple lookup tables, and are used by Thames, Midlands, South West and Southern Regions. Simpler rules of thumb may also be used; for example, if the river level at a gauging station exceeds a pre-defined trigger level, to initiate flood warning procedures.

Table 3.5. Model Application Issues: Correlation Methods

Issue	Main Advantages	Other Issues To Consider
Data Requirements	• Entirely data-based.	• Good range of high flow/level data are needed to apply to a site, with multiple correlations requiring large numbers of flood events
Suitability For Real Time Use	• Not computationally intensive (for example can be used manually or programmed into the telemetry system) and are robust • No initial conditions are required, therefore an excellent back-up for other forecasting systems	• Obviously rely on all upstream gauges used in the correlation operating reliability and providing good quality data during an event
Assumptions And Uncertainties	• Assume a unique relationship between upstream and downstream levels or flows (single correlation) or a predictable relationship in terms of magnitude/timing from any external inflows e.g. from tributaries (multiple correlations) • Usually calibrated only on peak values but can sometimes perform reasonably on the recession • Rely on level or flow data only so not affected by the uncertainties in rainfall measurements and forecasts • Level level correlations do not require a rating (although are then susceptible to changes in channel conditions etc whereas flow-flow correlations are more transparent in treating volume and rating related problems and so are easier to maintain)	• To provide a sufficient lead time, a reliable river level gauge(s) is (are) required upstream. Hence the approach may not be applicable to small or rapidly responding or complex catchments • Correlations based on peaks will not forecast the shape of the downstream hydrograph consistently particularly the rising limb • Cannot easily account for external influences in a reach e.g. tributary inflows, floodplain flows, gate operations, reservoirs, snowmelt runoff etc. • The timings of peaks can be sensitive to the direction of storm movement, tributary inflows and spatial variability of rainfall requiring several equations to cope with differing combinations of conditions. • Results may be dependent on a rating equation if performed in terms of flows with the usual doubts about extrapolation at high flows; however, if levels are used then at site problems (e.g. seasonal weed growth, datum changes, changes to the river channel) can affect the correlation
Suitability For Extreme Events		• Generally approximate with a limited range of applicability - results cannot be extrapolated beyond the calibration data extremes with confidence
Ease Of Use – Calibration	• Usually easy to calibrate. Can be calibrated in a spreadsheet or with a calculator	• Multipart correlations, or correlations dependent on rainfall distributions, seasonal effects etc require more expertise to develop and, possibly, specialist software
Ease Of Use - Operational	• Readily understood and analysed by Flood Warning staff • Easy to use operationally and no specialist training is required. • Expert user comments/help and confidence limits may be added to graphs/computer displays and are easy for users to interpret.	• The results can look very precise, despite the fact that they are approximate. A danger is a false level of confidence.

3.3 Rainfall Runoff Models

Rainfall runoff models represent the process of conversion of rainfall to flows across a range of soil types, topography and other factors. They can be used independently to forecast flow, or, more commonly, in combination with other model types, e.g. routing or hydrodynamic models to generate model inputs. Rainfall runoff models may be driven by observed rainfall (by radar or raingauge) giving longer lead times than models based on flows alone, with the potential to increase forecast lead times by using rainfall forecasts as a model input (although with a further reduction in Accuracy). Due to these uncertainties, rainfall runoff models are rarely used to issue warnings without the use of a backup trigger at the site and/or real time updating, although this situation is changing as experience with these models increases across the Agency. The "Guidelines on Rainfall Measurements and Forecasts" discuss the accuracy of raingauge and radar rainfall measurements and forecasts in detail.

Typically, rainfall forecasts for up to 1-2 hours ahead are used in Real Time Models, with a current maximum value of 6 hours ahead available from the Met Office. The associated "Guidelines on Rainfall Measurements and Forecasts" provide detailed information on the types, accuracy and sources of rainfall measurements and forecasts available to the Agency. Some models may also require estimates for antecedent soil moisture which can be estimated on a continuous basis (e.g. soil moisture accounting) or derived from observations and models on an event basis.

Rainfall runoff models may be lumped, semi-distributed or fully distributed:

- Lumped rainfall runoff models (such as the unit hydrograph) use a single rainfall value as a model input at each forecasting time step and implicitly assume rainfall to be uniformly distributed across the catchment.
- Semi distributed models typically divide the catchment into a small number of homogeneous zones which contribute to the flows in the main channel further downstream.
- Distributed models account for the spatial variability of rainfall by subdividing the catchment into small sub-units (often a regular Cartesian grid): an approach that is possible with a dense rain gauge network, but better suited to high spatial resolution remotely sensed data such as weather radar rainfall data.

All operational rainfall runoff models currently used in the Agency are lumped and semi distributed models, although exploratory studies have investigated the practical issues associated with using distributed models with radar data and digital terrain models, with pilot studies in several catchments (National Rivers Authority, 1994: Environment Agency, 2000c).

The main types of rainfall runoff models which are presently used within the Agency are so-called black box models, and conceptual models. Black box models are mainly data based, in that they transform rainfall values to flows without considering the underlying physical processes in detail. Conceptual models, by contrast, attempt to represent these processes, although often in only a very simplified fashion. Conceptual models are also the normal choice for modelling rates of snowmelt, where this is significant.

3.3.1 Black Box Models

Black box models can relate flows at a forecasting point to flows further upstream, or more usually to a combination of rainfall and flows. When rainfall is included in the model, they are often categorised as a type of rainfall runoff model. The distinguishing feature of this approach is that the models are entirely data-based and have only a limited representation of physical processes (if at all).

a) Unit Hydrograph models

A unit hydrograph is defined as the direct response runoff resulting from a unit of effective rainfall falling uniformly over a catchment at a constant rate in a unit of time. The model assumes a directly proportional relationship between effective rainfall and surface runoff, and that the resulting flows are the sum of contributions from successive rainfall amounts (effective rainfall is total rainfall less a baseflow/infiltration component). Although more usually used for design flood estimation, this approach can also be used for flood forecasting, and is presently used in parts of EA Wales. The approach is also widely applied in the USA.

The model has the following basic assumptions:

- effective rainfall has a constant intensity within the unit of time;
- effective rainfall is uniformly distributed throughout the catchment;
- there is a direct proportional relationship between the effective rainfall and the surface runoff;
- the principle of superposition is assumed, so that if two successive amounts of effective rainfall are recorded, then the surface runoff hydrograph produced is the sum of the component hydrographs resulting from each of the rainfall inputs;
- the effective rainfall – surface runoff relationship does not change with time.

Table 3.6 lists some of the main issues to consider with the unit hydrograph approach.

Table 3.6. Model application issues: Unit Hydrograph

Main Advantages	Other Issues To Consider
The method is simple, robust and easy to understand, and also widely used by hydrologists.	Changes in percentage runoff during the course of an event can cause problems.
There are only a small number of parameters (for example, time to peak, peak flow, duration and percentage runoff in the UK's FSR approach).	In order to run in continuous simulation mode pre-processing of effective rainfall by considering SMD is required.
The method can be applied to ungauged catchments e.g. using Flood Studies Report (FSR) methodology.	Flow forecasts depend upon the quality of rainfall observations/forecasts.
	Unit hydrographs cannot be used on large catchments since the rainfall distribution over space is unlikely to be non-uniform.
	Unit hydrographs are applicable only when channel conditions remain unchanged and catchments do not have appreciable storage.

b) Transfer Function Models

A transfer function is a type of time-series model originally popularised by Box and Jenkins (1970). Flow at time t (Q_t) is related to past flow and rainfall through m flow parameters and n rainfall (R) parameters (giving a model with structure (m,n)). A pure time delay (τ) can be incorporated into the model structure to lag the impact of rainfall on resultant flow. The form of a linear transfer function model is shown in the following equation:

$$Q_t = a_1 Q_{t-1} + a_2 Q_{t-2} + \ldots + a_m Q_{t-m} + b_1 R_{t-\tau} + b_2 R_{t-1-\tau} + \ldots + b_n R_{t-n-\tau}$$

where:

Q = flow
R = rainfall
a_1, a_2, a_m = flow parameters
b_1, b_2, b_n = rainfall parameters
τ = pure time delay

The parameters of a transfer function rainfall runoff model can sometimes be interpreted with respect to catchment dynamics (e.g. partitioning of flow between fast surface and subsurface runoff and slow sub-surface runoff, percentage runoff, etc.). However, this is by inference rather than directly as with physically-based or conceptual models (Young and Tomlin, 2000).

Transfer functions of this form have been developed in the North-West, South-West and Anglian Regions. However, the models used an input of total rainfall and in some cases tended to perform poorly when applied to independent verification or test events, particularly in catchments with a significant baseflow component or dry catchments. This resulted in a lack of confidence in model performance that has limited their operational use.

Because of these problems, both South West and North West Regions use a variant of the simple linear transfer function model known as the physically realisable transfer function model (PRTF). The PRTF approach was developed by Han (1991) to address the problems of stability in model output by constraining the model structure and parameters to produce a positive and non-oscillatory (physically realisable) model output. The PRTF model has three additional parameters to adjust the shape, timing and magnitude of the impulse response. At present, these parameters cannot be automatically updated through the course of an event but may be set manually, either prior to the onset of an event or during an event. South-West Region is currently experimenting with a two-stage calibration as a means of developing a look-up table for selecting the parameters based on catchment antecedent conditions (see the example Factsheet in Appendix E).

Transfer function models can use either forecast flows or observed flows when running in real time. In the latter case, whilst updating the model state through the course of an event provides a powerful self-correction capability, over-reliance on state (and parameter) updating to counteract the inadequacies of a linear model in simulating a non-linear process is regarded as unwise. An alternative approach, and that advocated widely by researchers, is to use a non-linear transfer function model. In essence, all that is required is to use a non-linear function in series with a linear transfer function model to pre-process total rainfall to effective rainfall. Two approaches which are currently being investigated are described in Factsheets in Appendix E.

c) Artificial Neural Networks

Artificial Neural Networks search for patterns in flood event data such as flood wave travel times. The application of neural networks for modelling hydrological systems has received increasing attention from the research community in the past two decades (e.g. Khondker *et al*, 1998). Although no neural network models are applied operationally for flood forecasting, the North-East region of the Agency recently funded the Agency's first trial of artificial neural network models – a trial that included the winter 1999/2000 period. The development of the models for this project is also described by Kneale *et al.* (2000) and the results are presented by Cameron *et al* (2001). North West Region is currently exploring the possibility of commissioning a neural network development project for the River Weaver.

3.3.2 Conceptual Models

Based on classical soil moisture accounting principles, conceptual rainfall runoff models typically transform rainfall into catchment runoff by cascading the inputs through a series of conceptual reservoirs. Each conceptual reservoir only bears an idealised physical resemblance to real reservoir processes and these techniques do not account for momentum/energy processes. There are many types of conceptual rainfall runoff model available commercially, plus several in-house models developed by the Agency. Snowmelt may also be included as a component of a conceptual rainfall runoff model (see Factsheet RTM12 in Appendix D).

At the most sophisticated level, rainfall runoff models may be fully distributed on a grid based pattern; that is, runoff is estimated for each grid and then accumulated to estimate total river flows. This approach is well suited for use with high resolution gridded input data; for example, weather radar data.

At a simpler level, the once popular Isolated Event Model (IEM) and Input-Output-Storage (ISO) model are also still used operationally in a few locations. These simple models relate catchment outflows to the quantity of water stored in the catchment, with the rate of change of storage given by the difference in “inflows” (i.e. rainfall) and outflows. This simple model structure also often appears as a component in more complex conceptual models, with variations between models arising from the relationships assumed between storage and outflows, the derivation of effective rainfall based on catchment conditions and – in some models – the introduction of time delays to simulate the impacts of routing.

Table 3.7. Model application issues: Transfer Function Models

Issue	Main Advantages	Other Issues to Consider
Data Requirements	• No catchment details or physical parameters required • For linear and PRTF models, the only inputs required to the model are rainfall and flow time series. If a pure time delay is introduced, the delays due to channel routing can be simulated in an approximate manner	• Non linear components, which convert rainfall to effective rainfall, may require other data types e.g. soil moisture, air temperature although flow-based alternatives are available
Suitability For Real Time Use	• Can be parametrically efficient ('parsimonious') • Very robust method requiring event data only and minimal run times	• Possible for unrealistic oscillations/values to occur unless (a) the model is well structured and calibrated or (b) a structure is chosen which is constrained to provide physically realistic results (e.g. PRTF) • When observed flows are used in the model, usually very reliant on the quality and reliability of the upstream gauging station (but tolerant to raingauge problems)
Assumptions And Uncertainties	• If observed flows at the Forecasting Point are included in the model then preliminary state updating of forecasts is automatically included (although manual adjustments may also be required during the event) • No specialist catchment knowledge or information required to develop the model • In Agency practice, typically used to relate flows to rainfall but can be used for any time series input (level, flow, rainfall) and output (level, flow), including use of a pure time delay to represent routing, although implementations in terms of level require care (due to possible backwater effects at gauging stations etc) • Parallel pathway versions aim to simulate the relative contributions from fast response surface runoff and slower response baseflows	• Better performance may be achieved if the model is driven by effective rainfall, introducing the uncertainties arising from rainfall separation based on catchment conditions (which is an active research area) • Purely data based, so no possibility of transfer between catchments (as with, in principle, a conceptual model, for example) • Some effective rainfall parameterisations can produce physically unrealistic effects if not structured correctly e.g. effective rainfall greatly exceeding total rainfall or negative values in impulse functions
Suitability For Extreme Events		• Models cannot necessarily be extrapolated with confidence beyond the extremes of the dataset used in the original calibration
Ease Of Use (Calibration)	• Quick and cost effective to calibrate. Calibration can be undertaken using specialist software such as MATLAB® • Formal assessments of uncertainty are easily performed during calibration due to the stochastic nature of these models	• For some model structures, higher levels of expertise and experience are required to produce models that are both accurate and mathematically stable for the full calibration range • Model parameters are entirely data based and so it is not easy to have a 'feel' for the range in which the optimum values might lie
Ease Of Use - Operational	• Can be state and/or parameter updated in real-time. Error correction can also be applied	• Some models used in the Agency at present require manual intervention to update them in real time requiring considerable experience or well specified procedures (although others update purely from telemetered observed flows)

Table 3.8. Model application issues: Conceptual Rainfall Runoff Models

Issue	Main Advantages	Other Issues To Consider
Data Requirements	• Despite the model complexity, data requirements may be for no more than catchment average rainfall and observed flows	• Can require types of data (e.g. evaporation) which are not easily available in real time (although daily or seasonal values may suffice) • Usually requires a reasonably accurate high flow rating equation to convert flows to levels
Suitability For Real Time Use	• Operationally proven and a strong track record. • Many models automatically take account of prior catchment conditions if run on a regular ('continuous') basis (e.g. daily) and can be also used for the full flow range e.g. low flow forecasting • Considerable tolerance to instrument failure if several raingauges used	• Require regular running to keep stores initialised meaning that special start up routines are needed if the model has not been used for some time (although commercially available packages often handle this automatically) • May be intolerant to data loss if using weather radar or a single raingauge (unless backup data sources/profiles are designed into the package). Ideally, a model should be calibrated using rainfall data from the same source that will be used as model input in real-time
Assumptions And Uncertainties	• Despite the conceptualisation of real runoff processes, several models have shown potential for transferring parameter values to catchments with similar characteristics but less data (although not used operationally at present) • At present the best approach to modelling snowmelt generated runoff • For operational use, due to the conceptual nature of these models, the decision whether to use semi distributed or lumped models should depend more on whether there is a consistent relationship between rainfall and runoff in a subcatchment rather than being predicted beforehand from a detailed analysis of soil types, vegetation, geology etc (although this can also help in making this decision)	• Despite the conceptualisation of physical processes, models are not truly physically based (and do not pretend to be). Fully distributed models are usually too data hungry and parameter intensive for real time use (although show promise if used with weather radar data) • Sometimes a similar 'model fit' can be achieved using different combinations of parameters, or model optimisation procedures may converge on a local (non optimum) parameter set • Depending on the model structure, may not be optimised for flood flow conditions, and some parameters may be almost redundant in these conditions. Also, fast flow pathways may not be correctly calibrated if only low to medium flows used in the calibration
Suitability For Extreme Events	• Due to the conceptual basis, model forecasts can sometimes be extrapolated with more confidence than purely data based forecasts	
Ease Of Use (Calibration)	• Conceptual basis readily comprehended by classically trained hydrologist • Some packages have automatic optimisation routines, which help to make the model calibration more approachable for non specialists • Most models have established calibration guidelines or tools • Wide range of models available commercially and in universities	• May have many parameters (parameter intensive) and the models can sometimes be 'information-hungry' • Usually these models require commercially produced specialist calibration software • There is a wide choice of potentially suitable models with no definitive benchmarking studies or standards available for evaluating the relative performance (although refer to Environment Agency, 2000c)
Ease Of Use - Operational	• Can be very simple to use operationally if an appropriate run time environment is available • Error and state updating can both be used	

3.4 Routing Models

Routing models typically forecast flows or flows and levels at a point on the basis of observations made further upstream. They provide one of the most reliable forecasting techniques available and are often a good first choice if sufficient warning time can be achieved. Routing models represent a physical process (flow in a river channel) which can in principle be modelled by suitable approximations to the mass and momentum conservation equations, and usually offer higher performance than rainfall runoff models, although with shorter forecasting lead times. Routing models are conventionally classified according to the extent to which they approximate the mass conservation and momentum (St Venant) equations for one dimensional flows in a river channel.

At the simplest level, correlation based approaches can provide a cheap and simple method for estimating peak levels or flows in the absence of any complicating effects (e.g. floodplains, significant tributary inflows), although sometimes multiple correlations, or several curves (e.g. representing variations in the location of peak rainfall), can be used to represent effects such as tributary inflows. Black-box transfer function models can also be used to provide data-based routing and have many similarities to the more physically based methods when these are expressed in their computational form i.e. finite differences.

However, hydrological routing methods should (in principle) provide increased accuracy since they attempt to approximate the full equations of motion, and so provide some representation of the effects of wave speed attenuation and resistance on the shape of the hydrograph. These methods include the Muskingum-Cunge method (Cunge, 1969), the Variable Parameter Muskingum-Cunge version (VPMC) (Price, 1977, Tang *et al.*, 1999) and Kinematic Wave models. Cunge (1969) showed that, with an appropriate choice of length and time steps, the Muskingum Cunge method provides a good approximation the linear convective/diffusion equation, which in turn is a simplification of the full St Venant equations used in hydrodynamic routing models. The variable parameter version of this method removes the restrictive assumption of constant wave speed and diffusion parameters by allowing these parameters to vary with discharge, as do some variants of the kinematic wave model (although at the expense of introducing some empiricism to the solution).

Lateral inflow estimates are often required in combination with more sophisticated modelling routing techniques. Early research (Price, 1973) suggested a typical runoff from small streams etc in a reach of about 0.05 cumecs per kilometre length and this is a useful starting point if no other information is available. For larger inflows, a more explicit empirical approach is to assume inflows to be a proportion of flows at the upstream end of the reach or a hydrologically similar catchment, perhaps based on an area weighting of catchment areas and/or mean annual rainfall. Where tributary inflows make a significant contribution to flooding, their inputs may need to be forecast explicitly; for example, by correlations, routing or rainfall runoff modelling.

The Factsheets also provide several examples of the use of these methods within the Agency.

Table 3.9 Categorisation of Flow Routing Modelling Approaches

Category	**Description**	**Examples**
Storage routing methods	Volume conservation is expressed using a simple water-budgeting approach. Conservation of momentum is neglected.	Muskingum model (McCarthy, 1938)
Hydrological routing methods	Physical processes controlling volume conservation are accounted for but those controlling conservation of momentum are approximated	Kinematic wave (Lighthill and Whitham, 1955) Muskingum-Cunge (Cunge, 1969) Variable Parameter versions e.g. Muskingum-Cunge (Price, 1973, Tang *et al.*, 1999), Kinematic Wave (Moore and Jones, 1978)
Hydrodynamic (or 'hydraulic') routing methods	Physical processes controlling the conservation of volume and momentum/energy are accounted for using a numerical solution of the full St Venant equations for gradually varying flow in open channels (usually 1-D only)	1D and 2D variants (see below)

Table 3.10. Model application issues: Routing Models

Issue	Main Advantages	Other Issues To Consider
Data Requirements	• Can be applied without any surveyed cross section information or roughness estimates	• Variable parameter versions require a number of events covering the full flow range for calibration
Suitability For Real Time Use	• Low computing requirements • Proven track record in real-time application • Usually provide a stable solution over the full flow range (although sometimes unstable at the start of calculation and on steep slopes during the recession). More robust for real time application than a hydraulic model	• Obviously heavily reliant on the upstream gauge operating reliably (and providing good quality data) during a flood event
Assumptions And Uncertainties	• Work in terms of flow so can only predict levels at locations with rating curves. • By dividing a reach into discrete lengths, most models can handle tributary inflows (both magnitude and timing) and permanent losses/spillage from the system (e.g. washlands) in an approximate way which can sometimes be sufficient for flood forecasting needs (exploratory studies advised) • Usually require a rating curve to convert flows to levels at the Forecasting Point but some versions can jointly calibrate the model and the level-discharge relationship (in an approximate way suited for forecasting applications only) although this requires care if there are backwater effects etc	• Usually more successful on steeper channels where there are no backwater influences on flows • Cannot easily handle complex channels, operations at flow control structures etc • Results and model stability can depend on an appropriate choice of distance and time step
Suitability For Extreme Events	• Variable parameter versions can represent flood plain influences and wave speed/attenuation curves can sometimes be extrapolated for flows outside the calibration range	
Ease Of Use (Calibration)	• Simple if automated calibration software is available	• Multiple reach application requires expertise and experience due to the need for internal parameter calibration, with results sometimes dependent on the timesteps and distance intervals chosen
Ease Of Use (Operational)	• Simple if a suitable system environment is available	

3.5 Hydrodynamic Models

In more complex situations, for example when flows and levels are affected by backwater effects or structure operations, unsteady hydrodynamic models should offer more accurate and site specific warnings than these other methods, particularly within the vicinity of structures and Flood Warning Areas, and in the tidal reaches of rivers. These models require accurate survey data, and higher quality inflow data, than other types, and so can be more expensive and time consuming to develop. The advantage of using hydrodynamic models include being able to explicitly represent the effect of flow control and diversion structures, to model confluence flows and multiple channels, and to estimate levels at sites with no river level recorder. Models can also be extrapolated outside the range of calibration with some confidence.

Also, in recent years, the Agency has commissioned the development of numerous 1-D hydrodynamic models for flood risk modelling and mapping ('Section 105 studies') and considerable potential exists for the conversion of these 'off-line' models to a form suitable for real time use. Hydrodynamic models are the recommended solution when backwater effects, tidal influences, operations at structures etc need to be simulated accurately i.e. where there is no unique relationship between levels and flows at the Flood Warning Area. They also provide the opportunity to investigate the potential impacts of, for example, bridge blockages through 'what if' scenarios.

In real time operation, hydrodynamic models are often combined with rainfall runoff models and simpler routing models and there are now several examples of such integrated systems in the Agency; for example on the river Eden in North West Region (variable parameter routing+hydrodynamic) and on the Tees in North East Region (conceptual model+kinematic wave+hydrodynamic). Integrated models are also used overseas; for example, following the catastrophic floods on the Rhine in the mid 1990s combined real time rainfall runoff and hydrodynamic models are being developed for the Rhine and Meuse basins in Germany and the Netherlands combined with a GIS-based flood inundation mapping system.

The Factsheets also provide examples of operational real time 1-D hydrodynamic models.

Table 3.11. Model application issues: Hydrodynamic Models

Issue	Main Advantage	Other Issues To Consider
Data Requirements	• Data requirements can be as simple as a forecast inflow hydrograph (but obviously can include complex downstream boundary conditions, tributary inflows etc)	• Models are data/information hungry - (from channel and floodplain survey to structure information and control rules for sluice gates and pumps) • Information on structure operation is sometimes required but often structures are manually operated in an 'ad hoc' manner, requiring parameterisation of operational control rules within the model (although, under flood conditions, structures will often be fully opened/closed and so exert no control on flows)
Suitability For Real Time Use	• Several Regions (including North West, Thames, North East, and Anglian) have already successfully implemented a limited number of these models in real time with promising results	• A relatively new technology for real-time operation in the UK (although used overseas for some years) • HD models are much more expensive to produce than any other sort of forecasting model (although all Regions have Section 105 models which might be converted to real time use-with more work required for steady state models)
Assumptions And Uncertainties	• Models represent the physical features and hydraulic processes of the whole river system and are capable of representing the influence of hydraulic structures. • Can be used both for routing flows down to a Flood Warning Area and for a more detailed local model (although routing over long channel lengths can be expensive in terms of survey data) • The real time operation of hydraulic structures can be modelled explicitly, as can storage reservoirs and other large	• There are limitations with the accuracy of a 1-D model when modelling complex flow areas (such as large floodplains), ideally requiring use of more complex and data intensive 2-D models (project WSC12 " Real time out of bank inundation models" initiation documents, March 1999) • For real time use the model may need to be 'slimmed down' by decreasing the spatial resolution, replacing structures by simpler representations etc and may need reviewing/recalibrating. Also, the stability

	influences on flow. • Floodplain depths and flows can be modelled explicitly. • Abstractions and discharges due to pumps, water treatment works, river flow intakes etc can be modelled explicitly • Provide detailed information (e.g. mean water velocities and levels) at nodes along the modelled reach which is especially important where knowledge of peak levels is required to high accuracy (e.g. relative to flood defences), or of water surface profiles (e.g. to support real time inundation mapping)	of the model on start up will need to be investigated if the model is not run continuously. The original model should also have been optimised for flood flows, e.g. a low flow model may have different survey locations and may omit floodplains etc • Control rules may be complex and may introduce run-time problems associated with the control algorithms • Feedback problems involving a structure controlling flows which are forecast using a hydrodynamic model are one of the most challenging in hydraulics sometimes requiring expert advice and possibly research and exploratory modelling studies before real time implementation • Updating can be a challenge to implement particularly when there are several telemetered gauging stations within the spatial extent of the model, and because any changes made can propagate both upstream and downstream, and may violate mass conservation assumptions
Suitability For Extreme Events	• Models incorporate channel and floodplain geometry and hence extrapolation of the model beyond the calibration extremes is sometimes possible with a high level of confidence provided that the underlying assumptions (e.g. 1D representation) are not affected	
Ease Of Use (Calibration)	• There is extensive experience in the UK in using these models for off-line studies and Section 105 models can often be converted to real time use. Several well proven and supported commercial packages make the calibration process straightforward • Despite their complexity, hydrodynamic models can easily be interfaced to simpler routing and rainfall runoff models and also simpler (e.g. 1D) estuary models • Parameter estimation is well documented and relatively straightforward	• Expertise is required to build models and to decide on how to incorporate hydraulic structures and other factors (e.g. lateral inflows) within the model • Expertise is also required to convert off line models to real time use, with issues surrounding stability (e.g. when starting from low flows, or with sudden gate operations), resolution (it may be necessary to 'slim down' the model extent, or number of sections, to achieve an acceptable run time) and updating procedures (with great care needed not to degrade the forecast).
Ease Of Use (Operational)	• Simple to operate if a suitable run time environment is available	• The large amount of information provided (multiple forecasting points, gate operations etc) requires a carefully designed user interface and training if forecasters are to make best use of the information provided

3.6 Integrated models

Routing and hydrodynamic models may of course be combined with rainfall runoff models although the forecast quality will then be dependent on the accuracy of the rainfall measurements/forecasts in addition to the errors in the routing procedure. Model results will also generally be constrained by the range of calibration data available, although some conceptual, variable parameter routing and hydrodynamic models provide the potential to extrapolate model data beyond the extremes of the calibration data set (the ‘calibration envelope’) as well as coping with artificial and other influences on flows.

There are several examples of integrated rainfall-runoff and routing models in use in the UK (for example, in Midlands and North East regions) and some specific examples are provided in the Factsheets in Appendix D and E. Models may cover the whole catchment or selected parts where the benefits, or data, justify use of a model e.g. there may be a “lower catchment” model for a major town near the coast.

Figure 3.1 illustrates a simple modelling situation in which flows are forecast at an upstream location using a conceptual rainfall runoff model, and then routed downstream to a Flood Warning Area for input to a hydrodynamic model.

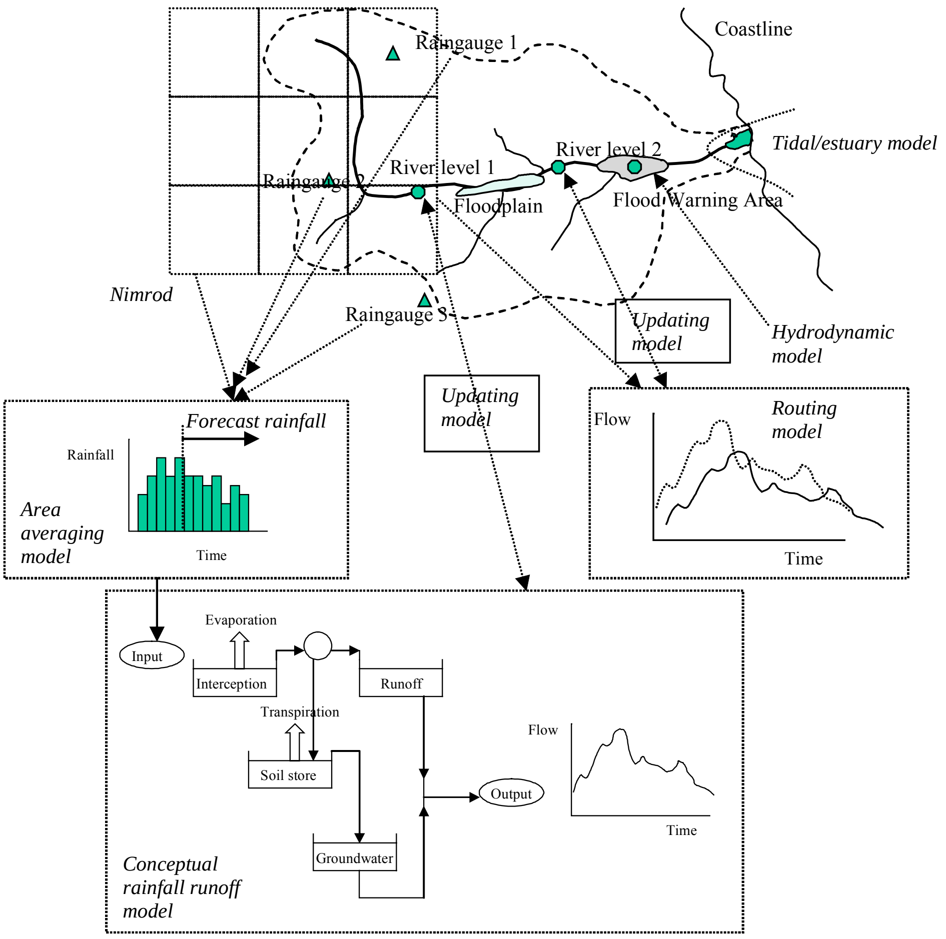


Figure 3.1. A simple example of an integrated model in which a conceptual rainfall runoff model forecasts flows for input to a routing model and a hydrodynamic model

3.7 Real Time Updating

When forecasting river levels and flows in real time, it is inevitable that there will be differences between the forecast and observed values and it is now common practice to update forecasts based on observed values for all except the simplest types of model. Updating provides the potential to significantly improve the accuracy of model outputs and is one of the main factors which differentiate Real Time Models from other types of model (e.g. simulation/design models).

Real time models will also often include an updating option, in which observed levels or flows at a telemetered gauging station are used to correct the forecast based on the differences observed up to the time of observation. Most models except for empirical models are capable of being updated.

Updating methods can either be integrated into the model itself (by updating the state or parameters of the model to account for differences between observed and forecast flows), or be a separate model which is calibrated and run independently of the main model (error correction). State and parameter updating is usually performed in terms of flows whilst error correction can apply to levels or flows.

Since updating often improves the accuracy of forecasts, the assumption should be to use updating unless there is a good reason not to (e.g. poor data quality). This is particularly so for hydrodynamic models, since updating is usually performed for several sites simultaneously, so the impacts of data errors at any one site are less severe.

However, for simpler models (e.g. routing, rainfall runoff), for which corrections rely on data for a single site, updating should only be used on a well calibrated and structured model, and not as a way of accounting for a poor or inappropriate model. Also, since problems can sometimes occur (e.g. if errors are random, or non-modular or backwater effects are important at the updating sites) then, if possible, the system environment used should allow the original and updated forecasts to be compared together in order to decide if the updated values are plausible.

If the data used for updating are suspect, then it may be necessary to restrict updating to a particular range of levels or flows in which values are considered to be reliable. Also, updating routines (particularly error correction routines) are often formulated in terms of magnitude errors, rather than timing errors, and assume that the forecast values will remain consistently above or below the observed value throughout the lead time of the forecast. In this case, updating is more likely to be successful if the timing of the peak is correct, implying that this should be a particular focus of model calibration if real time updating is to be used.

Certain types of model (e.g. transfer function models) can include updating automatically since they have the option to use observed flows up to ‘time now’ in generating forecasts of future flows, whilst others (e.g. conceptual models) usually require in-built facilities if state or parameter updating is required. Figure 3.2 illustrates the principles of updating in real time models for the case of an updating model which forces the correction to reduce to zero at the maximum lead time available.

Updating typically operates by comparing the simulated and observed time series at one or more gauging stations during the pre-forecast period in order to determine a correction to apply during the forecast period. This correction can then be applied:

- to the model output (error correction)
- to the model state (state updating)
- to model parameter(s) (parameter updating).

Other techniques include correcting the input data for assumed errors (especially rainfall data) and applying a timing error correction independently from the main updating routine (e.g. so-called pattern matching techniques in which a search is made for the timing correction which leads to a minimum least squares error between observed and forecast hydrographs).

Simpler techniques can also be used; for example, extrapolating the trend in errors by ‘eye’, or using computer based methods to distribute the error evenly over the lead time of the forecast, or to apply a time shift or scaling factor to the hydrograph to account for any apparent timing or magnitude errors. However, these subjective methods rely on the Duty Officer being able to make an appropriate adjustment during the event.

It should also be noted that updating may be counterproductive in some situations, for example, on the Witham catchment in Anglian Region, updating upstream of automatic control structures was found to cancel out the improved flow control by the structure. In some cases (e.g. when the high flow end of rating is suspect, or backwater effects predominate) it may be necessary to only apply updating over limited flow or level ranges.

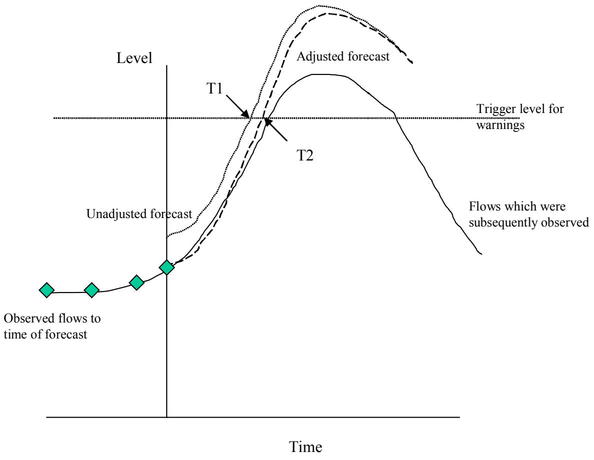


Figure 3.2. The principles of real time updating of forecasts – in this example levels are forecast to exceed the trigger level at T2 rather than T1 following adjustment by reference to the observed values (indicated by diamond symbols)

3.7.1 Error Correction

Error correction methods make use of the observation that time-series of errors from complex models are often highly auto-correlated (i.e. show persistence in flows). This means that errors can be modelled and predicted using statistical time-series methods, and this information used to improve future forecast accuracy. A simple type of error correction is simply to qualitatively adjust (or 'blend') the forecast values so that they match the observed values at time 'now' and the forecast values at the maximum lead time of the forecasts. However, more formal techniques are available based on statistical models and that is the approach discussed in this section.

Error correction is currently used in:

- Wallingford Software's FloodWorks product
- the current Midlands Regional Flood Forecasting System
- the CEH Kinematic Wave model (Moore and Jones, 1978)

FloodWorks uses auto-regressive moving-average (ARMA) models for error-prediction. The predicted errors are then subtracted from the model output to give an error corrected forecast. The principal advantages offered by error-prediction models are:

- they can be attached to any model simulation engine
- they can be used on any parameter (flows, levels, inflow volumes etc)
- they generate a completely independent output stream enabling both uncorrected and corrected forecasts to be viewed simultaneously
- the error prediction model parameters can be 'calibrated' separately from the simulation model parameters, using an automatic calibration tool.

The Midlands Regional Flood Forecasting System uses an error correction approach referred to as the 'Error Forecast Model'. The Error Forecast Model examines the difference between observed and simulated flows over a six-hour period prior to the time of forecast. Using an auto-regressive model, a prediction of how the error observed in this six-hour pre-forecast period will continue into the forecast period is made. The updated flow forecast is then calculated as the sum of the simulation forecast from the hydrological model and the predicted error. The duration of the forecast period over which the error correction is applied is determined as a function of the mean error compared to the mean flow during the six-hour pre-forecast period. The duration of updating is longer for small errors than it is for large errors.

In general, the error correction corrects the flow/level at the discrete forecast points and does not affect the internal state of the model. Sophisticated data-driven techniques can also be used for error correction such as artificial neural networks.

3.7.2 State Updating

Unlike error correction, state updating actually modifies the state of a model based upon the forecast errors and so is an intrinsic part of the forecasting model. The most common state updating technique is to replace the modelled flow value for a given time with the latest available flow observation, when the measurement becomes available (from the telemetry system).

This type of state updating is commonly used in transfer function modelling where it is relatively simple to implement, either by use of Kalman filters for linear models, extended Kalman filters for non-linear models or by simple state updating as discussed above. However, this can result in instability in the model state as it continually step changes to match the latest observations. To overcome this, empirical methods can be used in practice.

Some other examples of the operational application of state updating are provided by:

- MIKE11 Flood Forecasting module (MIKE 11 FF)
- Orange River ISIS model (South Africa) (Whitlow *et al*, 1998)
- Conceptual models as applied in Environment Agency North East Region

In hydrodynamic models, state updating techniques are more complex since they need to retain mass. Possible methods include distributing the error into the lateral inflows (if any) or at gauging stations, and correcting the inflows to the model for errors in phase and amplitude. For example, the updating routine provided by MIKE11-FF provides an illustration of how state updating can operate in an hydrodynamic routing model (see Factsheet RTM15 in Appendix E). The MIKE11-FF state updating module operates by adding or removing water from the hydrodynamic model network at locations defined by the user. These are normally gauged locations at which real time measured time-series are available.

The routine is initially calibrated against historical floods, the calibration being used to determine the following:

- Parameters such as the Analysis Period (i.e. the period prior to forecast used to compare simulated and observed values) and time constants for both the Analysis Period and the Forecast Period (i.e. the rate of decay of the correcting discharge)
- The order in which updating is carried out. Updating is best carried out along the dominant direction of flow. In rivers the sequence of updating will be in a downstream direction. In tidally influenced waters the downstream points will need to be updated first. For complex fluvial / tidal models the order of updating is inevitably a compromise
- The number of iterations required to stabilise the updated model. Iteration is required to ensure that the influence of updating at all locations is dissipated correctly throughout the model. Since the effects of updating at one location will influence the calculation of 'correction flows' at another, the model will need to be iterated to ensure that the optimum correction flows are determined for each updating point. Iteration is particularly important at updating sites where water level and flow are affected by both upstream and downstream influences.

When operating in forecast mode the routine moves the simulated time series both along the time axis and the discharge/water level axis until the best agreement between the simulated and measured time-series is achieved. The best agreement is defined as the minimum of the sum of square deviation between the simulated and measured time series over the Analysis Period. Once a best agreement has been determined the model is able to assess the phase and amplitude error in the Analysis Period, and from there can compute the inflows (or outflows) to be applied to the HD model network to take the errors into account during the Forecast Period.

This approach has the following advantages:

- Because it operates by correcting the water balance at locations within the model, the effects of updating are seen throughout the whole model, and not just at the updating point
- It is able to specifically identify and correct for phase errors, an error that is not so well accounted for by simpler error correction routines
- It operates on both water level and discharge. When updating on water level the correction discharge is computed indirectly using cross section conveyances in the vicinity of the updating point
- The operation of updating points can be sequenced to reflect the direction of flow (e.g. downstream to upstream in tidal reaches)

3.7.3 Parameter Updating

Parameter updating is a technique whereby the value of one or more of the model parameters is changed (updated) based upon observed data.

This approach compares observed and predicted values through a pre-forecast period and adjusts model parameters so that the forecast period produces more accurate results. This approach can be used for simple linear transfer function rainfall runoff models by updating the rainfall parameters at each forecast time step by attributing forecast error to error in the rainfall parameters used (which may or may not actually be the case). However, it should be recognised that it is difficult to identify in real time whether an error in the forecast is derived from data error or the model itself.

In hydrodynamic models the source of error is often hard to identify (channel roughness, floodplain flow, overbank flow, structure operation and so on). Parameter updating is not therefore used at present although research is on-going to investigate the identification and impact of parameter correction on forecast results. As with state updating, Kalman filters can also be employed for parameter updating.

Table 3.12. Model application issues: Updating Techniques

Issue	Main Advantages	Other Issues to Consider
Data Requirements	• Only requires observed levels or flows at the Updating Point	• Updating using poor quality data (e.g. high flow ratings) can degrade the quality of the forecast
Suitability For Real Time Use	Error prediction • Non-interactive or invasive with model, therefore less risk of model crashing and not requiring intervention by the Duty Officer • Will often improve the prediction and unlikely to make it worse at short lead times • Generates a completely independent output stream enabling both uncorrected and corrected forecasts to be viewed simultaneously • Probably the most widely used approach in UK practice State Updating • Because updating adjusts the water balance of a model, its effects are dissipated	Error prediction • Implausible behaviour may occur if errors are random in time rather than following the underlying assumption of persistence in flows (particularly around the peak flow) Parameter updating • Little used in UK practice to date

	throughout the entire model, thus improving forecasting performance between updating points	
Assumptions And Uncertainties	• The underlying assumption is usually that the observed data are more accurate than the forecast at 'time now' (requiring good quality data), and that forecast errors vary in some predictable manner (e.g. in terms of magnitude, timing error, data input errors, model parameterisation etc) Error prediction • Can be attached to any type of model. Can be used on any parameter (flows, levels etc) • Unlike other updating methods, often assumes that the updating correction will decay towards zero at the maximum forecasting lead time State updating • Reinitialises the model at each time step based on observed flows, taking away some of the doubts about model initialisation at the start of an event • Can help to account for errors in rainfall measurements and forecasts when used in rainfall runoff models • This is the natural way to update transfer function models and the ISO/IEM class of conceptual model (although both error correction and parameter updating e.g. via a rainfall gain factor are possible) Parameter updating • Can correct in real time for an inappropriate model calibration	• Feedback effects can occur when forecasts which have been updated are subsequently used to guide the operation of flow control structures (operated manually or, especially, automatically) • Most updating methods cannot handle purely random errors well (but flow persistence means that often this is not a problem except, unfortunately, around the peak for some events) Error prediction • Short term correction only – simulation will decay back towards the predicted values as forecast period increases. State updating • For some types of model e.g. physically-based conceptual models, hydrodynamic models, there can be several possible ways of implementing state updating, with extensive testing needed to prove the chosen method to avoid unanticipated results Parameter updating • Raises many questions about which parameter should be updated, and how, for different types of error between observed and forecast flows • The implication for any model which attempts to represent physical processes in a catchment is that the model calibration changes during an event (e.g. conceptual and most routing models) suggesting that the model should be recalibrated rather than using updating to solve the problem
Ease Of Use (Calibration)	Error prediction Error prediction model parameters can be 'calibrated' separately from the simulation model parameters, using an automatic calibration tool	

3.8 Local Models

In many situations, forecasts may only be required at a single location, or Forecasting Point, in the Flood Warning Area, which will typically be a telemetered river gauging station. Forecasts of levels at this location are then assumed to be a good guide to the likely locations and severity of flooding throughout the Flood Warning Area, and are possibly used in conjunction with maps of likely areas of flooding for different flows/levels at that point.

However, if the Flood Warning Area is zoned, defended, or has other complicating factors (e.g. structures, complex channels), it may be desirable to forecast at more than one location. This will require a local Real Time Model, in addition to the model (or models) which provide forecasts down to the site from locations further upstream.

For extensive Flood Warning Areas (several kilometres or more) a routing approach might be used, but otherwise the main options for local models are correlation models, hydrodynamic models and simple linear interpolation of levels or flows between Forecasting Points. A hydrodynamic model will normally be required for high risk/high accuracy locations, or where the river level profiles vary significantly between events (e.g. due to structures, backwater effects etc). Hydrodynamic models can of course also be used for routing flows down to the Flood Warning Area.

Some typical examples of Forecasting Points within a local model might include:

- Gauging stations – a location where river levels and/or flows are measured
- Flow control structures – barrages, sluices, diversion weirs etc
- Potential flooding locations – points at which flooding may occur e.g. low points in flood defences

If real time updating is required, then at least one Forecasting Point must be at a gauging station, and ideally this will be within the Flood Warning Area.

Local hydrodynamic models are also the prime candidate for real time flow control problems, in which the model output is used to guide, or to automatically trigger, operations at a flow control structure. However, this type of feedback problem is one of the most challenging in Real Time Modelling and may require considerable exploratory work, or research, to implement successfully, particularly if there are any complicating influences between the control structure and the Forecasting Point (e.g. ungauged or regulated inflows, other structures).

3.9 Model calibration and recalibration

3.9.1 Model calibration

Before a Real Time Model can be used operationally it needs to be calibrated and validated against observed data. The procedures for calibration can be very model specific, and are thoroughly described in model manuals etc and Agency documentation (e.g. Environment Agency, 2002c). The aim of this subsection is therefore only to summarise a few general principles which apply to most types of model:

a) Use the same sources of input data which will be used in real time operation

Models should generally be calibrated using the same types of data which will be used in real time. For example, rainfall runoff models will usually make allowances for the representativeness of raingauge values (or otherwise) during the calibration, so the model will not perform as well if a different raingauge, or combination of raingauges, is used. Similarly, if weather radar data, or rainfall forecasts, are to be used, then the model should be calibrated against these data, with raingauges only used as a backup in real time in case of problems with the local radar (and ideally a separate parameter set should be used for raingauge driven runs). A model should also be calibrated and operated using a time step (typically 15 minutes or 1 hour for most Agency models) sufficient to resolve the features of the hydrograph – especially rising limb and peak, which is modelled.

b) Focus the calibration on the aspects of model performance required in real time

Obviously a model required for flood forecasting should include several significant flood events in the calibration even if some models (e.g. conceptual models) tend to be calibrated on a long run of data. This should include some events which are of the type for which the model is required e.g. prolonged frontal events, thunderstorms. For physically based models, it is important to be aware that, under high flow conditions, some aspects of the model may dominate performance which are not used (or important) at lower flows (e.g. floodplain models, fast response pathways). There can also be value in using model fitting statistics which focus on the aspect of the hydrograph which is thought to be most important (e.g. the peak, the volume, the timing, the rising limb) although models should generally represent the full flow range in order to give some confidence that processes are being modelled reliably. Section 3.2 in Part B discusses typical best achievable values for various performance statistics for different categories of model.

c) Use calibration events representative of current conditions

The selection of calibration events usually involves a compromise between the wish to use as many events as possible, and the knowledge that catchment characteristics, instrument calibrations etc can change over time, meaning that older events may not be so representative as recent events. For flood forecasting, a good example is that of flood defences, since new or raised defences can affect the hydraulic behaviour at a Flood Warning Area and areas downstream, and may also change the hydraulic performance at gauging stations. Also, recent floods may have altered river channel profiles, damaged instruments (which have now been replaced) and so on. Having selected a number of suitable events, several should be kept aside for use later in model validation (if there are enough events for this to be possible).

d) Double check data for large flood events

By their rarity, extreme events can lead to unsuspected problems which were not considered in the original instrument installation. For example, gauging stations may be bypassed at high flows, structures may have non modular flows, backwater influences may affect measurements at instruments which perform well at lower flows, raingauges may have significant discretisation errors etc. High flow/rainfall data should therefore always be quality controlled before use in calibration. A useful phrase to remember when calibrating models is ‘rubbish in, rubbish out’. Some types of Real Time Models (e.g. conceptual models) also require continuous sequences of data for calibration, but peak values may sometimes be missing due to instrumental problems during floods (e.g. damage by debris). The decision then needs to be taken whether to attempt to infill missing values with all the uncertainty this introduces (e.g. by correlation with a nearby station) or to reject the event from the calibration (with the risk of removing a high return period event).

e) Understand and document the limitations of the model

Most models require approximations so will inevitably not simulate every conceivable event. For example, a lumped rainfall runoff model may not represent extreme convective rainfall causing flood flows on a major tributary, or a fixed parameter routing model may not model the attenuation and travel time impacts of flood plain flows. This means that the model should be calibrated using a representative range of the types of event which it is capable of modelling, including any artificial influences, and excluding those which it cannot (however it is a useful exercise to see how it performs by using these events during the model validation, together with synthetic/artificially generated extreme events, to see if the output remains plausible). Under extreme conditions, flow modifications may occur which have never been recorded in the instrumental record (e.g. flood defences overtopping) and which were not considered in the original model calibration. Any limitations on model performance should be highlighted in Flood Warning Procedures and, if the facility exists, in the user interface for the operational model. Part B of this report provides additional information on sources of model uncertainty.

f) Assess the sensitivity and stability of the model to parameters and data

It is useful, if not essential, to assess the sensitivity and stability of the model output to variations in model parameters and input data to see if the output will remain reasonable under extreme conditions. For example, for a rainfall runoff model, the model might be tested against synthetic rainfall events of different extreme depth/durations, or a hydrodynamic model might be tested for combinations of inflows and downstream boundary conditions outside the range used in calibration. If a hydrodynamic model is ‘slimmed down’ for real time use, any changes in its performance should also be carefully examined and documented. It is also desirable to assess the sensitivity of results to typical ranges for the key model parameters; for example, many models can be calibrated both against individual events, to assess the range of parameter values obtained, and against all events, giving a single parameter set for real time use. Part B of this report provides an introduction to methods for assessing and displaying model uncertainty.

g) Optimise model performance for the run time environment

Real time models are typically calibrated off-line and the resulting parameter values are then used in the operational system. However, some modern packages allow the model to be calibrated in a pseudo-run time environment, with parameters optimised for a specific lead time (e.g. 1 hour ahead), and the updating routines calibrated jointly with the model parameters. Intuitively, this calibration for purpose would be expected to yield more reliable results in operational use than the classical approach. If a network of models is being used, then it is obviously desirable to assess the performance of the overall system using representative types of input data, as well as the performance of individual models within the system.

h) Use an appropriate level of quality assurance for model development

Quality assurance procedures document the process by which data were checked and models were calibrated, validated and implemented in the run time environment. Reports by HR Wallingford (1993), Environment Agency (1998a) and Environment Agency (2002c) give a good indication of the types of procedure which should be followed which will typically involve:

- Registering incoming information– reports/computer files/parameters etc
- Auditing – identify reports and computer files with dates/versions/user etc
- Checking – spot checks/graphical comparisons/benchmarking etc
- Testing – for robustness to data loss, model failure etc
- Verification – against calibration data
- Validation – against independent data
- Archiving – all documents generated, datasets used, models
- Approval –at each step

The usual data quality checks used for design modelling studies also apply to Real Time Models; for example, spot checks of survey data. Also, any changes during or after the model development should also be registered within the quality assurance system.

3.9.2 Model Maintenance

Like most of the Agency's other assets (instruments, flood defences etc), Real Time Models require regular reviews of performance and occasional recalibration to maintain optimum performance. It is strongly advisable to set a regular interval and procedure for such reviews (e.g. annually and following major events) so that they can be built into routine work schedules and do not get overlooked.

If this is not possible, routine post event analyses of the types outlined in Part B of this report should give early warning of problems, particularly if the analyses are broken down into performance statistics for individual models, rather than for the whole forecasting and warning system. An increase in false alarm rates, and reduced Reliability, can also indicate possible problems with model calibration.

The following factors can influence the need for model recalibration (and as with the original calibration should be documented as part of a quality assurance procedure).

a) Changes to the input data calibrations

Models implicitly account for the errors in instrument calibrations and representativeness by trying to minimise forecasting errors based on the measured data (as opposed to the true values; which can never be measured exactly). Therefore, if an instrument calibration factor (e.g. a rating curve), or the instrument itself, changes, then model performance should be evaluated and possibly recalibrated against the new data. If using weather radar based products (e.g. Nimrod, locally adjusted radar, radar-only forecasts) it is important to note that the Met Office does not presently timestamp or version control hardware or software improvements for external customers such as the Agency. The performance of models calibrated on radar-based products should therefore be reviewed at regular intervals and information on the latest changes (and their implications) obtained from the National Flood Warning Centre.

b) Catchment and floodplain developments

As indicated in the previous section, developments to flood defences and within the catchment can change the conveyance of channels and the performance of river level recorders. More generally, any major change to operating rules, structures etc, channel improvements (dredging etc) can have an impact on model performance and may indicate the need for recalibration, whilst temporary river works can degrade model performance for the duration of the works.

c) Impact of large flood events

High flows can wash away instruments, damage structures and change the bed profile of a river. Model performance should therefore always be reviewed as part of the post event analyses and, if found lacking, the model can be recalibrated including the data for the new event (and any other recent events since the last calibration).

d) New versions of models

The best models will be supported and maintained with regular upgrades offering new functionality resulting from research and other developments. However, before including a new version in an operational system, its performance should be evaluated against a number of representative existing models of the same type to assess whether the upgrades have affected performance. This might also be a good opportunity to consider whether to make any other changes to the overall system which might take advantage of this new functionality.

4. DAMAGE AVOIDANCE METHODOLOGY

4.1 Introduction

Damage avoidance analyses provide one possible approach to deciding whether a new flood warning system is viable, or if an existing system should be improved. For any given Flood Warning Area, the options for improving the situation can include:

- Improving flood defences for the whole area (or for individual properties)
- Improving the dissemination of flood warnings (e.g. AVM, sirens etc)
- Making better use of flow storage/diversion possibilities (e.g. reservoirs, washlands)
- Installing additional instrumentation (e.g. raingauges, river level gauges)
- Making better use of existing data and rainfall forecast products
- Developing new or additional flow forecasting models (e.g. rainfall runoff models)
- Improving existing triggers for flood warnings (or establishing new triggers)
- Improving the calibration of existing instrumentation (e.g. extending rating curves)
- Improving the ability of a gauging station to measure high flows (e.g. raising side walls)

The first three of these options lie outside the scope of this project and are not discussed further. For the resulting flood warning system, if warnings can be provided in time then cost savings (benefits) can arise from:

- Being able to reduce or eliminate damage by moving possessions or setting up temporary flood defences (sandbags etc) and emergency maintenance (e.g. clearing culverts)
- Warning motorists, transport operators, utilities etc sufficiently early to take avoiding action
- Avoiding loss of life (people, animals) either during the event or from subsequent problems (illness, stress etc)
- Making more efficient use of Agency and other staff resources (e.g. the emergency services)

The costs and benefits can then be combined into a formal cost-benefit analysis to assess whether the proposed improvements or installation are economically justified and to help with deciding between different modelling solutions.

Ideally, the benefits would be estimated separately for each Flood Warning Area using post event survey data from many events and/or hydraulic modelling, and taking account of the current condition of any flood defences, the depth and velocity distributions across the floodplain, and the situation regarding each property at risk (threshold level for onset of flooding, likely damage etc).

In practice, such detailed analyses are usually not practicable or necessary, and for this project it was agreed that the methodology would be based on that developed by the Middlesex University Flood Hazard Research Centre (FHRC) (and described in National Rivers Authority 1995b). This methodology underpins the national Flood Warning Investment Strategy and has also been adopted for the recent Agency Project W5-010 "Forecasting Extreme Water Levels in Estuaries for Flood Warning Purposes" (Environment Agency, 2001b).

However, it should be noted that the the method does not consider any additional benefits arising from reducing factors such as loss of life (people, livestock), disruption to transport, and the stress/illness etc arising from the event or wrongly evacuating hospital patients/the elderly during false alarms etc. It also does not take any account of the operational benefits which might be obtained through introduction of new or improved Real Time Models; for example, having the information available to make better use of washland or reservoir storage to minimise flooding, improvements in scheduling the mobilisation and standing down of staff etc.

Instead, the method aims to give a first estimate of the annual damages which can be avoided by installing or improving a flood warning system (i.e. the so-called opportunity benefit), offset by the cost of property owners taking any avoiding action (time lost etc).

4.2 Summary of the model

In this approach, flood forecasting benefits are taken to be the damages avoided from providing effective flood warnings. The prime purpose of flood warning is to ensure public safety but a secondary and important economic effect is to enable the public to mitigate against flood losses by moving property which might be damaged to a level above the eventual flood level.

The methodology provided in the Guidelines is intended to give estimates for the opportunity benefit on a site specific basis for a new or improved forecasting system. Typically a site will be a Flood Risk Area or an existing Flood Warning Area. A spreadsheet to help with performing the calculations is available from the National Flood Warning Centre.

The method is summarised as:

$$\textit{Actual flood damage avoided} = (P_f \times P_i \times P_a \times P_c) \times \textit{Potential flood damage avoided}$$

where:

P_f = ***Reliability**, ie probability that an accurate forecast is made and is disseminated*
P_i = *probability that a member of the individual household will be **available** to be warned*
P_a = *probability that the individual is **physically able** to be respond to the warning*
P_c = *probability that the individual **knows how to respond** effectively*

The last three terms relate to the ability of the public to respond to warnings and fall outside the scope of the study (although suggested values are provided below). However, the reliability P_f is one area which can be improved through using better data, forecasting models etc and this term is defined as the product of:

- the probability that a flood is accurately forecast
- the probability that it is effectively disseminated

P_f is therefore analogous to (but not equal to) the 'Hit Rate' or 'Probability of Detection' which is the proportion of observed flooding events forecasted successfully. As with many other performance measures, P_f decreases with increasing lead time due to the inherent uncertainties in forecasting at longer lead times. P_f may also depend on the definitions of flooding and the interviewing format/questionnaires used (for example; does flooding start at the property boundary, garden, outhouses, garage, or inside the main property with "carpets wet"?).

Since the reliability is defined in terms of actual performance, and must be estimated from post event surveys, this places the designers of flood warning systems in a 'chicken and egg' situation in that, at present, a system cannot be designed to meet a given reliability. Research has been proposed as part of this project to address this situation. For design, the usual approach (which has been adopted here) is to assume a target reliability and to assume that, by following best practice modelling procedures, the reliability will increase towards or exceed the target value.

More generally, damage reduction clearly increases with the minimum warning time provided (i.e. the time between the dissemination of a flood warning to the public and the onset of property flooding). Also the percentage of damage saved will generally increase with respect to the eventual depth of flooding (provided that possessions have been raised well above this level).

The following tables give the damage reduction potential for two example lead times (2 hours and 8 hours) assuming 100% reliability of the forecast; 100% reliability of dissemination and that the availability, ability and willingness of the public to respond to a warning is 100%. These assumptions lead to estimates for the potential damage savings, which are later adjusted to account for values of less than 100%.

Table 4.1. Residential Potential Flood Damage Reduction (£/property) June 2000 price base

Depth of Flooding (m)	Total Potential damage (£) [1]	Damage Reduction for those responding			
		2 hours warning	*% of total damage*	*8 hours warning* [2]	*% of total damage*
1.20	11,657	2,949	*25*	4,744	*41*
0.90	9,815	2,484	*25*	4,181	*43*
0.60	8,344	2,111	*25*	3,521	*42*
0.30	6,448	1,631	*25*	3,037	*47*
0.10	2,907	735	*25*	1,099	*38*
<0.10	880	223	*25*	333	*38*

[1] Building Fabric and Inventory; economic damage; mean of short and long duration

[2] It is widely recognised that damage savings rapidly diminish after 8 hours

Table 4.2. Commercial Potential Flood Damage Reduction (£/m2) June 2000 price base

Depth of Flooding (m)	Total Potential damage (£) [1]	Damage Reduction for those responding			
		2 hours warning	*% of total damage*	*8 hours warning* [2]	*% of total damage*
1.00	443	90	*20*	173	*39*
0.60	278	55	*20*	104	*37*
0.30	194	34	*17*	66	*34*
0.15	126	2	*1*	14	*11*
0.00	0	0	*0*	0	*0*

[1] Based on average retail and related business but can be applied to any non-residential property (NRP)

[2] It is widely recognised that damage savings rapidly diminish after 8 hours

Tables similar to those above could be used with flood depth data to calculate potential damage savings for each property type affected by flooding. However, a simplified method is proposed which does not require knowledge of flood depths for a range of return periods or locations of individual properties within the floodplain.

In summary, as the property location is unknown at this scale of analysis, the algorithm assumes that any property within a flood-prone zone takes on the weighted flood damage characteristics for any property for each flood stage, irrespective of its location in the floodplain. The depth damage distribution for the successive return period flood events was calculated from 12,000 modelled property flood depths and a weighted annual average damage derived for each property type. For example, at June 2000 prices, the weighted annual average damage for a residential property is £1,054 assuming that its floodplain is unprotected. As Standard of Service (protection) improves, this weighted annual average damage reduces. For a 1 in 100 year protected floodplain the value falls to £19 per property.

Damage savings as a result of improved flood warning lead times are applied to the 'No Warning' data. The following table summarises weighted annual average damages for residential property for successive standards of protection from flood defences and the damage savings with successively improved lead-times:

Table 4.3. Weighted annual average damage estimates for residential properties

Existing Standard of Protection	Weighted annual average damage (£ June 2000 values)				
	No Warning	Damage savings with lead times (hours)			
		2	4	6	8
No Protection	1054.44	280.72	388.60	419.92	440.80
2 Year Standard	858.40	227.36	316.68	342.20	358.44
5 Year Standard	596.24	157.76	219.24	237.80	249.40
10 Year Standard	316.68	84.68	118.32	128.76	134.56
25 Year Standard	148.48	18.56	56.84	61.48	63.80
50 Year Standard	42.92	11.60	16.24	17.40	18.56
100 Year Standard	19.14	5.80	8.12	8.70	9.28
200 Year Standard	9.57	2.90	4.06	4.35	4.64

Similar data tables have also been derived for distribution related commercial activity (i.e. logistics and warehousing), retail, manufacturing, and an “other” category for use in the absence of any specific knowledge of the commercial property (also known as non-residential properties). The potential annual average damage avoided can be calculated from the damage avoided tables as a function of the number of residential properties and m^2 of retail, distribution, manufacturing and ‘other’ property categories, lead time and standard of protection. To calculate the actual annual average damage avoided, the reliability, availability, ability and effectiveness factors described below need to be used.

4.3 Definitions of performance factors

4.3.1 Reliability

The reliability measure, P_f ,combines the probability that a flood is accurately forecast and the probability that it is effectively disseminated. P_f is analogous to the ‘Hit rate’ (the proportion of observed flooding events which have been forecast). When assessing the economic benefits of a proposed flood forecasting method the existing and target (ie, with new method) hit rate will need to be estimated. If flood forecasting is currently not undertaken then the existing hit rate is zero. If there is an existing forecast then the hit rate should either be calculated from records of post event analyses or estimated using best judgement. The Flood Hazard Research Centre (National Rivers Authority, 1995b) suggests that, based on a limited set of case studies from 1986/87 and 1990, the mean value of existing reliability is about 45%.

The hit rate for new forecasting systems is harder to quantify but should lie between the value for the existing method and 100%. It should be noted that the hit rate will be constrained by the accuracy of the flow forecasts and the topic of forecast accuracy is discussed later in this report.

The hit rate will reduce as the warning time increases. This effect is demonstrated in the following table which relates to the Met Office’s Severe Weather Warning Service:

Table 4.4. Example of variations in reliability with warning time (Met Office Severe Weather Warning Service)

Lead time (Hours)	Current reliability (%)	Target reliability (+5 %)	Target reliability (+10 %)
1	80	85	90
2	75	80	85
4	70	75	80
6	60	65	70
8	50	55	60

4.3.2 Availability to be Warned

The availability factor, P_I , relates to the presence or absence of property owners/occupiers to receive flood warnings. This can range from 55% (loud hailers used) to 65% if police and/or flood wardens are involved in dissemination, with an increase to 80% if lead times are 6 hours or more (National Rivers Authority, 1995b). For commercial properties it is likely to be lower (45%) if lead times are 4 hours or less, but can rise to 80% for longer lead times. Suggested default values are therefore presented in Table 4.5:

Table 4.5. Suggested values for the availability to respond factor

Lead time (hours)	Availability to Respond
2	55%
4	65%
> 6	80%

4.3.3 Able to Respond

The ability to respond factor, P_a, reflects the proportion of elderly, disabled, ill, pregnant etc who are not physically able to respond to reduce damage. The suggested default value is 85%.

4.3.4 Effectiveness of Response

The effectiveness of response factor, P_c , relates to the proportion of respondents who are willing to respond and would effectively respond to reduce damages.

The suggested default values are set to 70% within communities who have a ‘low’ current Standard of Protection and 50% within communities who have a ‘high’ Standard of Protection (using 25 years as the boundary).

4.3.5 Combined Effect of Linear Model Factors

If the suggested default values for P_f , P_i , P_a and P_c are used then the approximate combined effect is to reduce potential benefit from actual benefit by the following percentages:

Table 4.6. Suggested combined value of factors

Lead Time (hours)	‘Low’ SoP <1 in 25 years	‘High’ SoP >1 in 25 years
1	26%	19%
2	25%	18%
4	27%	19%
6	23%	17%
8	19%	14%

Following the Agency's takeover of responsibility for flood warning dissemination in 1996, a target was set of a 50% product when combining these probability factors (from a 1996 product of less than 20%). DEFRA project appraisal guidelines do not give guidance on the likely product to convert potential damage savings to actual damage savings, but their example ranges from 14% (existing situation example) to 25% (with project example). The Agency 50% target reflects an improved flood warning service as, a combination of the effect of recent flood events, annual publicity campaigns and post-flood surgeries etc all assist to improve the product, from its assumed 1996 level of around 15%. One combination of factors to achieve the Agency's target of 50% is:

- Reliability 90% (default values: 45% to 80%)
- Availability to respond 80% (default values: 55% to 80%)
- Able to respond 85% (default value: 85%)
- Effectively respond 80% (default values: 50% to 70%)

To achieve these improvements will require improved reliability with increased lead times and a better informed and motivated public.

4.4 Costs of Mitigation of Flood Damages

There is a small cost associated with property owners and occupiers taking mitigating actions to avoid flood damage. This is equivalent to the resource (economic) costs of their time. This must be offset against savings for all flood warnings, even ones with low reliability as action, if it is taken, happens whether the flood occurs or not. Annual Average Costs are adjusted by the same factors of availability, ability and willingness to respond as annual average damage savings.

Recommended data on values of time and numbers involved in taking mitigation actions is provided in Table 4.7.

Table 4.7. Recommended default mitigation costs per property

Lead Time (hrs)	No. of Persons	Value of Time (£)	Time in Mitigation	Unit Cost (£)
Residential				
2	1.5	8.05	1	12.08
4	1.5	8.05	2	24.16
6	1.5	8.05	4	48.32
8	1.5	8.05	6	72.48
Commercial				
2	3	17.03	1	51.08
4	3	17.03	2	102.16
6	3	17.03	4	204.32
8	3	17.03	6	306.48

The default price base is April 2001 and data can be updated using the Retail Price Index (eg from www.devon-cc.gov.uk/dris/economic/retprice.html)

4.5 Calculation of Opportunity Benefits of Improved Flood Forecasts

A spreadsheet has been developed for calculating the opportunity benefits of improved flood forecasts and is available from the National Flood Warning Centre. The spreadsheet is designed so that a Flood Warning Area can either be divided into zones or lumped together. Zoning may be useful to enable spatially varying standards of protection, reliability and/or lead times to be explicitly considered.

The site specific input data required for the river as a whole or for each zone are:

- Reliability and lead time for the existing forecasting system
- Target reliability and lead time for the proposed forecasting system options
- Existing flood defence Standard of Protection in years.
- Number of residential and non-residential properties
- Total area (m^2) of retail, distribution, manufacturing and 'other'property

If total areas for each non-residential property category are not known, then a suggested conversion factor is to use an average floor area of 1825 m^2 .

Default values are provided for the remaining data required for the calculation and it is recommended that these values are reviewed and where there is uncertainty then as a minimum a simple sensitivity analysis undertaken. Economic data should be updated to reflect inflation and this can be achieved by selecting the RPI worksheet in the spreadsheet and updating the retail price index value (suggested source is: www.devon-cc.gov.uk/dris/economic/retprice.html).

The model then estimates the opportunity benefits (as an annual average value) of an improved flood forecasting system as:

Opportunity benefit = Target benefits – Existing benefits

Where:

$$\text{Target benefits} = (P_{ft} \times P_i \times P_a \times P_c) \times (PFDA_t - MC_t)$$
$$\text{Existing benefits} = (P_{fe} \times P_i \times P_a \times P_c) \times (PFDA_e - MC_e)$$

P_i = probability that individual will be available to be warned
P_a = probability that the individual is physically able to be respond
P_c = probability that the individual knows how to respond effectively

$PFDA_t$ = target potential flood damages avoided
MC_t = target mitigation costs
P_{ft} = target reliability (ie with proposed improvements)

$PFDA_e$ = existing potential flood damages avoided
MC_e = existing mitigation costs
P_{fe} = existing reliability

5. MODEL SELECTION ISSUES

5.1 General Approach

The guidelines present two main model selection approaches and this section outlines the basis for these approaches.

The first (Method A) is a purely qualitative approach suitable for a first assessment whilst the second method (Method B) is more detailed and aims to arrive at a reasonable compromise between:

- Technical Feasibility
- Implementatation Costs
- Damage Avoidance
- Model Accuracy and Uncertainty
- Data availability
- Operational Constraints

and other factors. The target audience throughout is taken to be Agency staff responsible for designing, commissioning, managing, operating and maintaining Real Time Modelling systems.

Typically, Method A would be used for a rapid appraisal of modelling solutions for a range of catchments (e.g. in a Regional review exercise) or to assist in the initial feasibility studies when considering improvements at, or establishment of, a Flood Warning Area. By contrast, Method B is aimed more at arriving at an initial design and an idea of the likely accuracy, and risks and uncertainties, in the proposed approach. The guidelines also indicate situations in which additional exploratory analysis and modelling work may also be required – for example, for high risk locations, or complex or costly modelling problems – called Method B+.

It must be emphasised that in many cases these approaches may lead to more than one solution, or to no single solution which meets all of the criteria. For example, the optimum modelling solution might not be cost effective, or might be cost effective but with no suitable system environment available in which to run the proposed model, or might be felt to be too unfamiliar or complex for Flood Warning Staff to interpret without additional training and on-line support.

As a result, as with many other types of design work, the design of a flood forecasting system is usually an iterative process, in which information is gathered, analyses performed, and design options evaluated and improved, to find the optimum solution in terms of costs, benefits, technical feasibility, and the expertise and availability of the staff who will set up and operate the system.

There are also a number of other generic factors which may affect the choice of model, which are introduced as “Application Issues” in the guidelines. These include:

- Model assumptions and limitations
- Model accuracy and uncertainty
- In-built functionality for post event analysis and reporting
- In-built functionality for data archiving
- Model calibration and recalibration requirements
- Other more subjective/non technical factors which can affect model selection

The guidelines provide a brief introduction to these topics but they are discussed in more detail in Part B of this report.

5.2 Sources of Information

The Real Time Modelling guidelines, and the associated Rainfall Measurement and Forecasting guidelines, are based on the results of previous Agency R&D studies, reviews of the international literature, exploratory modelling studies and feedback from the Project Board. They are believed to be the most comprehensive guidelines to date covering Real Time Modelling for fluvial forecasting problems, although previous reports have covered many individual aspects of the problem. In particular, the contributions from the following studies are acknowledged:

Environment Agency, 2000a *"Good Practice Baseline Review"* A recent general review of the entire detection, forecasting and warning dissemination process within the Agency with recommendations for best practice in each individual subject area.

Environment Agency, 2000c "C*omparison of Rainfall Runoff Models for Flood Forecasting, R&D Technical Report W242"* A recent and comprehensive review of the main types and 'brands' of rainfall runoff model currently used operationally within the Agency together with some international examples. Includes an evaluation of model performance on 8 catchments in England and Wales using perfect foresight of rainfall from raingauges, together with use of radar actuals for 3 of these catchments. This report builds on work presented in earlier reports which were also useful to this study (National Rivers Authority, 1993, 1994).

Environment Agency, 1998e "*Determining the freshwater flow needs of estuaries*" Although dealing with a range of simulation, rather than forecasting, issues, this report provides a good example of ways of presenting guidelines in complex situations where there are many factors to consider, and elements of the style appear in the present guidelines.

Environment Agency, 1998c *"A Best Practice Guide to the Use of Trigger Mechanisms in Fluvial Flood Forecasting"* An excellent review and draft guideline document on the setting of triggers for fluvial flood warning systems, and also covering selection of Real Time Models to some extent. Used internally within some Agency Regions but never issued in final form.

Environment Agency, 1997 *"Benchmarking and Scoping Study of Hydraulic Models, Technical Report W88"* A comparative study of the performance of a range of commercially available 'brands' of hydrodynamic model for a number of steady and unsteady flow problems.

Environment Agency, 1996 *"Evaluation of integrated flood forecasting systems"* A mid-1990s review of the modelling approaches and performance of the Agency's operational flood forecasting systems. Includes the basis of a performance estimation technique developed further by Midlands Region and this project.

National Rivers Authority, 1995a *"Review of the Optimum Accuracy of Flow and Rainfall Forecasting, R&D Note 433"* The first in a linked series of three reviews of flood forecasting systems during the mid-1990s (together with Note 463 on cost benefit analyses and Note 464 on weather radar). Provides a useful high level overview of flood forecasting in the UK and internationally.

National Rivers Authority. 1995b *"An Assessment of the Costs and Benefits of Fluvial Flood Forecasting. R&D Note 463"* Linked to R&D Note 433 above, this report sets out the economic analyses used to assess the costs and benefits derived from fluvial flood forecasting in England and Wales.

Reed, 1984 "*A Review of British Flood Forecasting Practice"* Although written more than 15 years ago, this review remains relevant today, with many of the models described still in operational use and some still at the research stage.

In general , where recommendations from these (and other) reports are general knowledge, no reference has been made to the report in the guidelines; however, where specific or new results are discussed, then the original reference is cited.

PART B - MODEL PERFORMANCE ISSUES

Along with cost, ease of use, availability of a suitable system environment etc, the issues of modelling assumptions and accuracy will often influence the choice of model. Part B reviews current knowledge about model performance based on the international literature and recent Agency R&D studies (Chapter 1), and presents the findings from some exploratory modelling studies aimed at providing a preliminary idea of how errors in input data and model calibrations feed through into forecasts of levels and flows and how this information can be analysed and presented (Chapter 2). The main findings from this review and modelling work are then presented in Chapter 3 together with background on how these results are implemented in the guideline document.

1. REVIEW OF THE CURRENT SITUATION

1.1 Introduction

This Chapter discusses the following issues related to model performance:

- Sources of model uncertainty (Chapter 1.2)
- Methods for assessing the performance of models (Chapter 1.3)
- Methods for dealing with forecast uncertainty (Chapter 1.4)
- Indicative performance of models (Chapter 1.5)
- Performance of operational systems in the Agency (Chapter 1.6)
- Post event analysis techniques (Chapter 1.7)
- Methods for Assessing Forecasting Uncertainty (Chapter 1.8)

1.2 Sources of Model Uncertainty

No model provides a perfect representation of physical processes and some processes are more difficult to model than others (e.g. the conversion of rainfall to runoff). Inaccuracies in input data (rainfall, flows etc) can also have a major impact on model performance. Table 1.1 summarises some of the main sources of errors in Real Time Models.

Table 1.1. Some of the main sources of uncertainty in Real Time Models

Main cause	Source	Example
Model input data	Errors in real time data	Impacts of poor exposure/siting of raingauges, non modular flows or flow bypassing gauging structures in high flow conditions
	Errors in the accuracy of the data used for calibration	Uncertain extrapolation of the high flow ends of rating curves, low resolution/inaccurate survey data
	Change in input data streams or catchment/channel characteristics	Using radar data when a model has been calibrated on raingauge data (or vica versa), temporary loss of telemetered data from some sources, improvements or changes to rating curves, channel changes or improvements etc
	Events outside the calibration range of the model	Model applied to situations outside the range of the data against which it was calibrated
Model calibration and other errors	Assumptions/structure of the model	All relevant physical mechanisms not included in the model (e.g. floodplain flows)
	Approximations in the model	Approximations to the governing equations of motion etc (if used at all)
	Model resolution	Time steps, grid lengths etc are insufficient to resolve the spatial and temporal scales of the event (floodwave, storm etc)
	Poor model performance in real time	Oscillations or physically unlikely flows
	Operator errors	Problems or misconceptions in calibrating or running the model

Calibration issues can be very model dependent and are discussed later for various categories of model, whilst the issues of input data errors are discussed in the remainder of this section. The main sources of uncertainty to consider are in:

- Rainfall measurements and forecasts
- Catchment antecedent conditions
- The high flow ends of rating curves

The first two of these problems affect rainfall runoff models (if used) whilst rating curve problems can affect both routing models (at both ends of a river reach) and rainfall runoff models (when predicted flows are converted to levels at a Forecasting Point).

The "Guidelines on Rainfall Measurement and Forecasting" discuss the main sources of errors, and likely accuracy, of rainfall measurements and forecasts in detail whilst Table 1.2 provides a summary of the main conclusions regarding the recommended uses of rainfall values in real time modelling.

Table 1.2. Some indicative uses of Rainfall Measurements and Forecasts in the Flood Warning process

Techniques available	**Use in Real Time Models ?**	**Use for Flood Watch ?**	**Use to issue quantitative warnings ?**
Raingauges, Nimrod actuals, locally adjusted radar	Yes	Yes	Public/all
Nimrod forecasts, radar-only forecasts up to 2-3 hours ahead	Yes	Yes	Public/all
Nimrod forecasts beyond 2-3 hours	Yes (especially for 'what if' runs	Yes	Prof. partners, Agency only
Heavy Rainfall Warnings	Indicative or 'What if' runs	Maybe	Prof. partners, Agency only
Daily Rainfall Forecasts	Indicative	Maybe	Agency only

The actual accuracy in any given situation depends upon:

- The type of rainfall event (frontal, convective, orographic etc)
- The detection/forecasting method being used (raingauge, radar-only, Nimrod, locally adjusted radar etc)
- The size and location of the catchment (topography, distance from nearest radar if relevant)
- The spatial and time intervals being considered

and other factors. These issues are discussed in the "Guidelines on Rainfall Measurement and Forecasting" but, as a rule of thumb, if the appropriate technique is used for a given situation, accuracies in hourly catchment rainfall accumulations of 10-20% are typically obtained for rainfall actuals, with comparable accuracies for a forecast lead time of up to 1 hour but dropping off rapidly beyond 2-3 hours. These values all apply to the types of frontal events which often cause flooding in the England and Wales, and errors for convective storms are larger (and with current technology such storms cannot usually be detected until they have started, which gives very short lead times for a typical storm duration of 1 hour).

Regarding catchment antecedent conditions, as with rainfall this is a quantity which is highly variable spatially. Rainfall runoff models often rely on estimates for the condition of the catchment (saturated etc) to estimate the "effective rainfall", which is a representation of the rainfall which, after infiltration etc, and possibly subtracting a baseflow, is available to generate surface runoff. Like the effective rainfall, the catchment antecedent condition is a conceptual quantity and a number of ways are used to parameterise it (e.g. soil moisture deficit, catchment wetness index). The main Real Time Modelling techniques used within the Agency at present are:

- Continuous soil moisture accounting based on rainfall, evaporation, runoff and infiltration estimates (usually intrinsic to conceptual models and an option for transfer function models)

- Assumption of a constant or varying percentage runoff during the event
- Parameterisations based on estimating conditions from an indicator of catchment conditions at the start of a flood event (air temperature, baseflow etc)

The Met Office's MORECS product can also provide initial conditions on a weekly basis for a 40km grid (and the new Met Office MOSES product will provide hourly data on a 5 km grid; see the "Guidelines on Rainfall Measurement and Forecasting"). In practice, there are considerable uncertainties in all of these approaches and the errors are usually absorbed into the model calibration. For models which do not already include these facilities (e.g. some transfer function and simpler models), the main modelling decision to take is then usually between:

- Using only total rainfall (not effective rainfall) – possibly suitable for saturated or low permeability catchments (exploratory studies advised)
- Assuming constant percentage runoff during an event – unrealistic but simple to implement and works in some situations (exploratory studies required)
- Continuous accounting during an event – the preferred approach if computing resources are available but only worthwhile if variations in catchment conditions are believed to influence flood flows significantly during an event

For rating curves, it can often be difficult to obtain high flow gaugings (since extreme flood events are rare) and hydraulic influences may affect the rating (e.g. non modular flows at structures, backwater effects). Many of these problems can be reduced or eliminated by choice of appropriate instrumentation and careful siting of instruments. There is also a range of methods for extending rating curves and an R&D project "Extension of rating curves at gauging sites using hydraulic models" should recommend the latest approaches and is due to report in 2003. For model calibration, the usual approach is either to extrapolate or extend the existing curve, or to limit application of the model to flows for which the curve is known to be valid.

1.3 Methods for Assessing Model Performance

The measures used to assess the performance of models are usually different from those used to decide if a forecasting system meets the high level targets of Reliability and Timeliness, and a wide range of statistical and other measures are available which fall broadly into the following categories:

- Hydrograph characteristics
- Threshold crossing performance
- Graphical comparisons

Here, the hydrograph is the variation in river levels or flows with time at a point during each flood event, and thresholds are levels which are important to the flood warning process (trigger levels, the top of flood defences etc). Assessments are usually performed for individual flood events, rather than for year-round values. For flood forecasting applications, threshold crossing measures are useful since often the performance of a system is judged in terms of its ability to predict whether critical levels will be exceeded (and the timing of this happening).

For all except the simplest models (e.g. level-level correlations), most operational rainfall runoff and routing models will also use some form of real time updating, in which the forecast values are adjusted based on observed values up to the time of the forecast. This contrasts with models running in simulation mode which normally use observations or design values of rainfall and/or upstream flows (possibly with other input data such as snow cover, temperature, catchment wetness etc).

The main features of the various types of updating schemes were described in Part A. However, from the point of view of characterising operational performance, it is desirable that, if updating is used operationally, then off-line assessments of model performance should also use the same updating scheme when generating hydrographs for comparison with the observed values i.e. the model calibration and updating procedures should be assessed together. A further issue, for off-line analysis of model forecasting performance, is which rainfall input to use – actual rainfall (i.e. assuming a perfect knowledge of future rainfall) or an 'historic forecast': the former will provide the best assessment of the ability of the model to forecast flows given the best possible inputs, whilst the latter will provide a realistic indication of actual operational forecasting performance.

Two approaches that can be used to assess forecasting performance are (Environment Agency, 2000c):

- **Fixed lead time forecasts** i.e. the pseudo-hydrograph constructed by drawing a line through the forecasts for each time step for a fixed lead time (leading to the production of up to *n* pseudo hydrographs where *n* is the maximum forecast lead-time;).
- **Fixed origin forecasts** i.e. the ensemble of the forecasts made through an event – one for each forecasting time, covering several time steps up to T+ *n*, the maximum forecast lead time

Assessments based on fixed lead time forecasts are simpler to calculate and interpret and are used almost exclusively (certainly in all Agency reports to date).

The types of assessments which can be performed are described in the remainder of this section, with much of the discussion based on Reed (1984), National Rivers Authority (1995a), Environment Agency (2000c) and Beven (2000).

1.3.1 Hydrograph Characteristics

These are measures which define how well the forecast hydrograph at a given lead time matches the observed hydrograph, and include the bias:

$$B=\overline{Q}_f-\overline{Q}$$

the root mean squared error:

$$rmse=\left(\frac{1}{N}\sum e^2\right)^{0.5}$$

and the R^2 statistic (sometimes called the Nash-Sutcliffe efficiency):

$$R^2=1-\frac{\sum e^2}{\sum (Q-\overline{Q})^2}$$

where Q is the observed flow, Q_f is the forecast flow, $e = Q - Q_f$ is the difference between observed and forecast flows, an overbar indicates a mean value, and N is the number of time steps over which the statistic is computed.

The bias gives an indication of systematic errors (e.g. consistent overestimation) whereas the rmse and R^2 errors given an indication of the accuracy with respect to random error. R^2 compares the variance in the model errors with that in the observed data, with a value of 1.0 being a perfect fit, and a value of 0.0 in effect saying that the model performs no better than just assuming the mean flow (negative values are also possible).

These measures all give an assessment of how well the forecast matches observed flows over the whole of the event (i.e. they are so-called ‘whole hydrograph’ comparisons). Other statistics are often used which focus on specific aspects of the hydrograph relevant to flood warning; for example the peak levels, peak flows, rising limb, total duration or total volume during the event, with the accuracy typically expressed either as an absolute value or, for flows, as a normalised value in the form of a ratio to the observed value or percentage error.

Due to the use of local datum levels used for most measurements of level, normalised values are usually not suitable for presenting information on the accuracy in levels, and timing errors also cannot easily be scaled (however, timing errors could be presented as a ratio to some timescale relevant to the problem, such as the duration of the event, the catchment time to peak or, for routing models, as a fractional error in the mean wavespeed for a reach).

1.3.2 Threshold Crossing Performance

For flood forecasting applications, it is also of interest to know how well a model is able to predict the crossing of thresholds such as flood defence and trigger levels. Many of the measures mentioned above for the whole hydrograph can also be adapted for this application; for example, duration, volume, time of crossing on the rising limb and on the recession (the 'all clear' time).

Another common approach is to calculate a so-called contingency table for each event, or for individual key features of the event (e.g. in an event with multiple peaks):

Table 1.3. Example of a Flood forecasting Contingency Table

	Threshold exceeded (observed flows)	**Threshold not exceeded (observed flows)**
Threshold exceeded (forecast flows)	A	B
Threshold not exceeded (forecast flows)	C	D

so that four measures of success can be defined as follows:

Probability of Detection (POD) = $A / (A+C)$
Critical Success Index (CSI) = $A / (A+B+C)$
False Alarm Rate (FAR) = $B / (A+B)$
Correct Alarm Rate (CAR) = $A / (A+B)$

Measures of this type have been widely used for many years in evaluating the performance of weather forecasts (e.g. Heavy Rainfall Warnings) but have been little used in flood warning applications except for research.

For flood warning, the Probability of Detection is analogous to the high level target of Reliability, but is based on forecasts of crossing a threshold, rather than feedback received from property owners who were flooded. Also, it does not include any notion of the depth or extent of flooding once the threshold has been crossed, which clearly both affect the 'Reliability' achieved. As with other measures of performance, the POD, CSI and CAR might be expected to decrease with increasing lead time, and the false alarm rate to increase

One problem which has been noted with this approach is that these values also depend on an arbitrary threshold value, and a more objective approach (Environment Agency, 2000c) is to accumulate values for A, B, C and D over a range of assumed thresholds covering the full flow range, and taking the ability to predict the times of threshold crossing to within a given tolerance as the measure of success. Overall values can then be calculated for POD, CSI etc which are independent of the threshold assumed (although still depend to some extent on the tolerances used to assess when a threshold is crossed).

1.3.3 Graphical Comparisons

Although quantitative measures of model performance are useful, so too are plots of forecast and observed flows. Plots are also suitable for a first appraisal of model performance before performing a more detailed analysis.

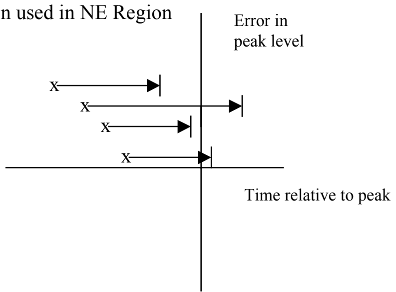
The most common types of plot used are:

- Time series plots of fixed lead time or fixed origin forecasts against observed values
- X-Y plots of peak observed values versus forecast values
- X-Y plots of absolute errors in timing and magnitude against peak level, flow or lead time

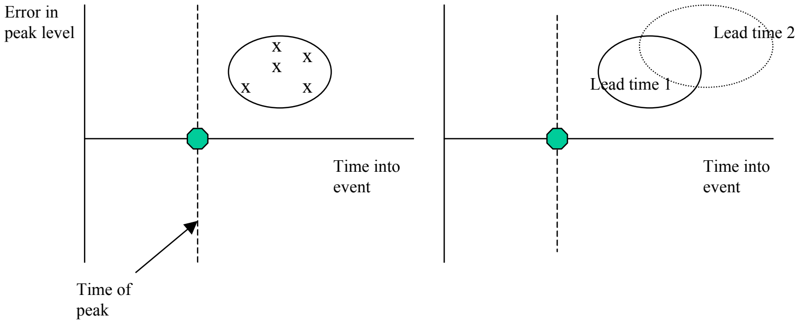
- X-Y plots of timing errors versus level errors (peak or threshold)
- Plots of measures of hydrograph characteristics against lead time

Figure 1.1 shows some examples of these types of plot.

a) Graphical presentation used in NE Region



b) Plot of timing and magnitude errors



c) Some classical methods of comparing forecasts at a fixed lead time

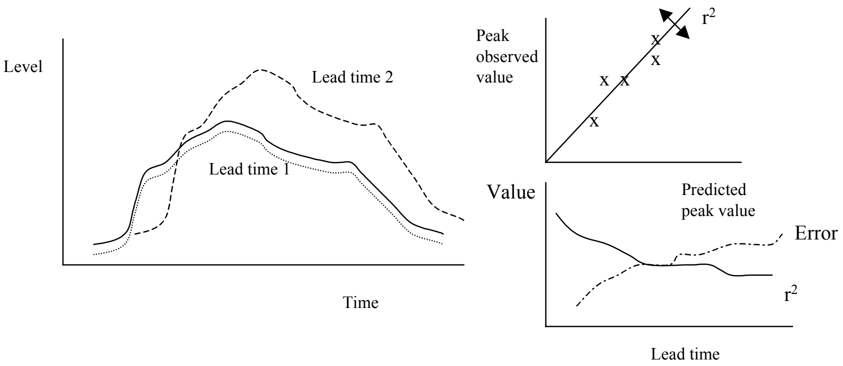


Figure 1.1. Examples of graphical presentations of forecasting errors

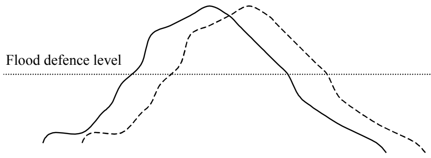
The first example (Figure 1.1a) shows one of the methods used by North-East region for post event assessments of model performance, and summarises how the accuracy of forecasts of the magnitude and timing of the peak changes in the time leading up to the peak. For each of the shorter horizontal lines, the x indicates the time origin of the forecast (relative to the time of the peak), the short vertical line indicates the forecast time of the peak, and the length of the line indicates the forecast lead time provided by the forecasting model. A ‘perfect’ forecast of the peak would lie on the horizontal axis with the short vertical line at the origin.

The second example (Figure 1.1b) shows an early version of one of the methods proposed within this project for assessing model performance. For a given lead time and forecasting point, errors in the level and timing of the peak, or crossing of a threshold, are plotted on an X-Y plot, with a value at the point marked with a circle being a ‘perfect’ forecast. Across many events, such plots should give a feel both for the typical magnitude of errors for that model (at that forecasting point and lead time) and whether there is any systematic error. From these data, a ‘deviation ellipse’ or ‘bullseye plot’ might be constructed centred on the point defined by the average timing and level error, with major and minor axes with a length proportional to some measure of the spread of errors e.g. maximum errors, standard deviation of errors. A separate plot can then show ellipses for different lead times to give an indication of how the model performance changes as lead time increases.

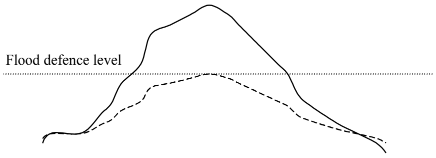
The final example (Figure 1.1c) shows a comparison of observed and forecast peak values, and in this case it is also possible to compute an r^2 error which can itself be plotted as a function of lead time, and should decrease with increasing lead time. The various measures of forecast error defined earlier can also be plotted as a function of lead time and their dependence with lead time will depend on how they are defined; for example, for measures such as CSI, POD or R^2, a maximum value indicates a 'perfect' forecast, so that values will generally decrease with increasing lead time, whilst for some other parameters (e.g. root mean square error, false alarm rate), values may increase with increasing lead time.

1.3.4 Comparison of Methods

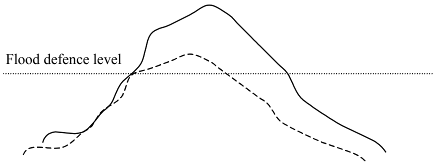
The methods discussed in this section can help with model calibration, in assessing uncertainty in real time, and in reviewing the performance of models after flood events, and different methods are appropriate to each task. Table 1.4 outlines some of the strengths and weaknesses of each approach and the rest of this section expands upon some of these points, whilst Figure 1.2 shows some qualitative estimates (high/low) for a range of typical hydrograph shapes.



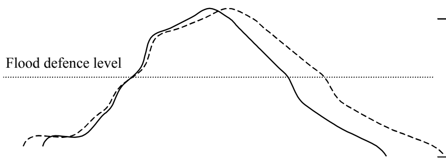
Whole hydrograph		Threshold crossing	
Bias	L	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	L	CAR	H
Peak error (timing)	H	Crossing time error	H
Duration error	L	Duration above error	L
Volume error	L	Volume above error	L



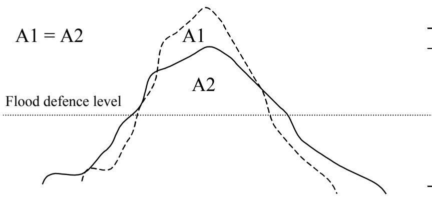
Whole hydrograph		Threshold crossing	
Bias	H	CSI	L
Rmse	H	POD	L
R^2	L	FAR	L
Peak error (level)	H	CAR	L
Peak error (timing)	L	Crossing time error	H
Duration error	L	Duration above error	H
Volume error	H	Volume above error	H



Whole hydrograph		Threshold crossing	
Bias	H	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	H	CAR	H
Peak error (timing)	H	Crossing time error	L
Duration error	H	Duration above error	H
Volume error	H	Volume above error	H



Whole hydrograph		Threshold crossing	
Bias	L	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	L	CAR	H
Peak error (timing)	H	Crossing time error	L
Duration error	H	Duration above error	H
Volume error	H	Volume above error	H



Whole hydrograph		Threshold crossing	
Bias	H	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	H	CAR	H
Peak error (timing)	L	Crossing time error	L
Duration error	H	Duration above error	H
Volume error	L	Volume above error	L

Figure 1.2. Examples of Performance Measures for Fixed Lead-Time Forecasts (Solid line – observed levels; Dashed line – forecast levels (L=Low, H=high)

Table 1.4. Strengths and Weaknesses of Typical Model Assessment Measures

Measure	Strengths	Weaknesses
Bias	Easy to interpret and calculate	Large errors can 'cancel out' giving a deceptively small bias Not normalised so cannot easily compare between sites and catchments
rmse, R^2	Emphasises outliers, which are often (but not necessarily) around the peak level/flow Normalised allowing comparisons between sites/catchments (not rmse)	Do not distinguish between over and under prediction or where in the hydrograph errors are most severe Implicit assumption of zero mean error with no autocorrelation can introduce bias if used for model fitting Do not distinguish between timing errors and magnitude errors
Threshold crossing measures	Views model performance from the forecaster's perspective	Difficult to compare between sites and catchments Values can depend on an arbitrary threshold
Graphical comparisons	Intuitive way of presenting results, particularly where errors are in timing rather than hydrograph shape Allow a quick inter-comparison of many results	Can be difficult to quantify and compare errors between sites/models, particularly when using scatter plots

For post event analyses, there are three main requirements:

- Long term monitoring of compliance with high level targets
- Formal post event reporting on individual events
- Routine and research studies of model performance

Although 'Flood Forecasting' appears as a topic in most post-incident reports, a recent review of Agency practice (Environment Agency, 2000a) notes that "there is no effective national standard for post event reporting at present" although Anglian Region is implementing the 'National Incident Reporting System' and some regions (e.g. Midlands, North East) have systems in place to monitor the success of flood forecasting and warning. Also, whereas calibration studies usually concentrate on the performance of individual models within the overall forecasting system, for post event studies it is usually the whole system (rainfall forecasts, data accuracy, rainfall runoff and routing models) which is evaluated.

A review of several internal post-event reports shows that graphical presentations are the most widely used approach; for example, time series plots of observed and forecast levels, or customised presentations such as that shown in Figure 1.1a from North East region. Single value indicators, such as the error in timing in peak levels, and in levels crossing a threshold (e.g. a trigger level or the top of a flood defence), also sometimes appear as plots or tables in post event reports of individual floods. If the river goes out of bank, or overtops flood defences, then additional parameters such as the extent and duration of flooding, and flooding depth, are also of interest.

Over the years, the Agency has also commissioned a range of R&D studies on model performance and these have used a wide range of performance measures; for example, hydrograph characteristics (e.g. R^2, normalised peak values), threshold crossing measures (e.g. CSI), and graphical comparisons (e.g. X-Y plots of peaks, and comparisons of the observed and forecast hydrographs). Results may be reported for all rainfall events, or for only a subset of events, to examine how the performance depends on the type of runoff generating event (e.g. convective, snowmelt, prolonged frontal) and the scale of the storm relative to the area and type of catchment.

For rainfall runoff and routing models, if the model uses real time updating then the model should ideally be evaluated in updating mode, rather than simulation mode, and typically fixed lead time forecasts are used. It is preferable to perform comparisons in terms of flow, rather than level, since then the results do not depend on a local (site specific) datum. Also, most forecasting models work in terms of flow, requiring a rating to convert these values to levels, which may be uncertain, or even undefined, at typical flooding levels, or if the river goes out of bank. Threshold crossing measures are of less interest for similar reasons, although one of the algorithms suggested earlier avoids the problem of having to specify a single arbitrary threshold value when evaluating model performance (Environment Agency, 2000c). Ideally, there would also be a direct correspondence between the measures used to evaluate model performance and the Agency's High Level Targets but infact there is only a tenuous link. For example, the POD at first sight appears similar to the Reliability term P_f, but further consideration suggests that Reliability also includes notions of levels/volumes above a threshold (relating to which properties flood). By contrast, the POD is a simple flood/not flood measure of performance.

The issue of combining measures across many sites or events is also a consideration, with an arithmetic mean not always being the most appropriate approach (alternatives including taking the median of all values, or to accumulate the statistic across many events before computing it e.g. for CSI or POD). It is also worth noting that small timing errors can adversely affect some measures (such as R^2) whilst having little effect on others (such as CSI or POD); for example, a forecast hydrograph which has the 'perfect' shape, but a delay in forecasting the peak, may score poorly on root mean square error, whilst obtaining a 'perfect' value for CSI. In meteorological research applications, this problem has been recognised in forecasting convective storms, where an otherwise good forecast of the rainfall distribution can appear poor when compared with rain gauge data due to a small error in tracking the overall movement of the storm. One solution which has been suggested is to translate the forecast storm to minimise the root mean square error and to present the tracking error as a separate measure (e.g. Ebert and McBride, 2000). A similar approach could be used in flood forecasting (i.e. translating the forecast hydrograph to 'overlay' the observed hydrograph, and presenting this 'translation' error as a separate measure) and has been trialled for real time updating of some models (e.g. Rungo et al., 1989).

1.4 Methods for Dealing with Forecast Uncertainty

Having accepted that all models have some degree of uncertainty, the two main ways to assess that uncertainty are:

- **On-line** (i.e. when the forecast is being made). Determining uncertainty on-line has the advantage of allowing the assessment to be made against observed levels and flows. However, forecasting systems are required to be robust, run models quickly and be easy to use which, in some cases (e.g. hydrodynamic models), can preclude the use of sophisticated assessment techniques on-line due to the run times required.

- **Off-line** (when the model is being calibrated and verified prior to use as a forecasting tool). Evaluation of uncertainty off-line allows a more comprehensive assessment to be made, although obviously only against historical data.

Techniques for assessment of uncertainty can range from simple adjustments to the model input data and parameters to sophisticated Monte Carlo and other simulation based approaches.

For example, ensemble forecasting techniques can be used and can range from simple comparisons of a range of 'what if' scenarios (e.g. no more rain, standard rainfall profiles) through to formal assessments of the distribution (spread) of forecasts based on a range (ensemble) of equally likely rainfall and inflow sequences, and possibly including uncertainty in model parameter values. Some examples of 'what if' scenarios include forecasts based on:

- Radar rainfall actuals
- Radar-only rainfall forecasts
- Combined radar and Numerical Weather Prediction model forecasts (e.g. Nimrod)
- Heavy Rainfall Warnings
- No future rainfall
- Rainfall continues at current intensity
- Rainfall continues at a rate derived from a previous major event

- Design rainfall profile

For weather forecasting, more sophisticated ensemble forecasting techniques have also been used operationally in the UK since 1992 for 10-day ahead forecasts, where an ensemble of 64 'forecasts' is used, assuming variations in input conditions and model parameters. Off-line ensemble analyses have also been used since the 1970s for reservoir design to estimate yield and derive operating rules (although this is more commonly called stochastic modelling), and have been used in real time in Thames region, for example, for reservoir operations during low flow conditions.

For flood forecasting applications, some examples of ensemble forecasting are those used in the American Extended Streamflow Prediction System (ESP), the simpler Anglian Region Flow Forecasting and Modelling System (AFFMS), and in the Mediterranean regions of France.

- ***Extended Streamflow Prediction System (ESP)*** is the uncertainty component of the Advanced Hydrological Prediction System, which is a forecasting system being implemented across the National Weather Service Forecast Centres in the United States. It uses an ensemble technique to create probabilistic river stage forecasts for the mid/long term time frame. Its principal use is to provide forecasts for the Spring snowmelt, by using the state variables of models at the time of forecast and up to 40 years of historical time series for model inputs (precipitation, temperature, potential evaporation) to determine a probabilistic forecast for multiple forecast points.

- In the ***Anglian Region Flow Forecasting and Modelling System (AFFMS)*** users are able to run a range of scenarios for model inputs (e.g. raingauge data only, radar data only up to the time of forecast, assuming no further rainfall or the current rainfall persists in the forecast period). This ensemble of information is used to draw conclusions as to the uncertainty associated with a forecast.

- In the ***Mediterranean regions of southern France*** (Obled and Datin, 1997) devasting floods occur in places most years with little warning. A combined deterministic/stochastic approach has been developed in which raingauge and radar data are used to estimate rainfall (together with radar-only and mesoscale forecasts), but are also linked to historical observations of rainfall patterns for the catchment; for example, the geopotential fields for pressure and temperature are used to assess the probability of heavy rainfall at lead times of 2-3 days (a similar approach is also used at the Cape Canaveral launch site). These techniques are also being evaluated at shorter lead times (a few hours), using stochastic modelling to link observations up to time now with likely future scenarios (again based on an historical archive). In real time, several hundred rainfall scenarios are fed into a rainfall runoff model to derive an average flow forecast and confidence limits on that forecast (with the option of conditioning the forecast by plausible limits on 1-2 hour ahead radar-only forecasts and on likely limits on daily rainfall for the catchment in the type of storm being observed).

Using procedures like these, estimates for model uncertainty (assessed on-line or off-line) can then be used by forecasters to support decisions on issuing flood warnings; for example, by assessing how confidence intervals (e.g. 95% values) vary with lead time which could then be displayed in real time in addition to the forecast levels or flows.

A more general summary of the issues involved in probabilistic/ensemble forecasting is provided by Krzysztofowicz (2001) who notes how this approach has now been widely accepted in meteorology, with techniques becoming available for a range of lead times from actuals and nowcasts through to long term rainfall forecasts. For hydrology some stated advantages for probabilistic forecasts are (in abbreviated form) that :

- They are scientifically more 'honest' than deterministic forecasts and allow the forecaster to acknowledge the uncertainty
- They enable an authority to set risk based criteria for flood watches, flood warnings etc with explicitly stated detection probabilities
- They appraise the user of the uncertainty enabling risk to be taken explicitly into account
- They offer the potential for additional economic benefits from forecasting

and the example is quoted of a councillor who, following a major flood on the Red River in 1997 (USA), noted that:

"….the National Weather Service continued to predict that the river's crest at Grand Forks would be 49 feet…if someone had told us that these estimates were not an exact science….we may have been better prepared"

(the actual peak was 54 feet).

In the Agency and elsewhere, operational flood warning services are still evaluating the requirement for some indication of confidence/uncertainty in forecasts, both of rainfall forecasts and stage/flow forecasts, although development of the underlying techniques has been a recurring theme in Agency R&D proposals for several years (see Part C).

Whether this approach would be of benefit in UK conditions remains to be evaluated, and has accordingly been proposed as one of the R&D themes arising from this project. However, it is worth noting that forecasts of thunderstorm rainfall are now routinely issued in television weather forecasts with an associated probability, with wide acceptance by the public of this approach.

The situation might be summarised as: on the one hand there is a pragmatic desire for a single definitive estimate of levels, whilst on the other, it is recognised that rainfall and runoff forecasting is inherently uncertain, and that it is only sensible to acknowledge this uncertainty through the production of ensemble flow forecasts and (hence) forecast uncertainty bounds or confidence limits.

1.5 Indicative Performance of Models

Real Time Models are just a variant of the simulation models which have been used in water resources and other off-line applications for many decades and a considerable body of knowledge has been built up on model accuracy both for simulation and real time use. Some key issues identified during early stages of this project were that:

- forecasting performance tends to be model(ling approach) and catchment specific
- forecasting performance can be event specific – even when the same model is used
- forecasting performance is partly governed by the skill in model calibration, which can depend upon the experience of the model developer and knowledge of the catchment
- most published estimates of model accuracy concern the performance of models in simulation mode, rather than in real time (updating) mode (which is the mode used operationally)

Despite these difficulties, this section reviews some of the main findings concering model performance, particularly where they relate to the propagation of errors from input data into model outputs:

1.5.1 Empirical Models

The main types of empirical model are level-level correlations, flow-flow correlations, and lookup tables. Lookup tables are usually only meant to provide a qualitative guideline on whether to issue a warning so will not be considered here. Regarding correlation approaches, these are widely used in several Regions but the success (or otherwise) usually depends strongly on the nature of the flooding problem; for example, results can be affected by tributary inflows in the reach over which the correlation is calibrated, or by out of bank flows.

In some Agency Regions, quite sophisticated models have been calibrated using different curves according to cumulative rainfall, location of peak rainfall, antecedent conditions, presence of snowmelt, tributary inflows etc, with variable travel times assumed, although it is often acknowledged that a more sophisticated model (e.g. a semi-distributed conceptual model and/or routing model) might handle these combinations of conditions better.

Also, although correlations are usually calibrated on peak levels or flows, they are often used to predict the exceedance of threshold levels (i.e. on the rising limb of hydrographs), where the accuracy can be poor. However, there are no general rules on applying correlations in this way since, for an empirical approach like this, the results are entirely data driven. Some studies (e.g. Reed, 1984) have also shown that correlations are more likely to successfully predict the recession of a hydrograph (useful for giving the 'All Clear'). Also, correlations will fail if the calibration data is not representative of the event; for example, if the flows go out of bank but all of the calibration data was for in bank flows.

For cases where correlations are felt to be useful, r^2 values of 0.9 or more have been reported (for example see the Factsheets in Appendix E), although often based on very limited data at the high flow end relevant to flood forecasting.

1.5.2 Rainfall Runoff Models

Rainfall runoff models attempt to model a complex physical process (conversion of rainfall to runoff) using data (areal rainfall) which can only be measured in an approximate way. Errors are therefore inevitable but operational experience has shown these models are often of sufficient accuracy for use in flood forecasting applications particularly when real time updating is used.

The main errors in rainfall runoff models arise from the input rainfall data and, assuming perfect foresight of rainfall, from spatial averaging of catchment rainfall and uncertainties in the structure and parameters of the model. Generally, forecast accuracy will decrease with increasing lead time, particularly if rainfall forecasts are used rather than rainfall actuals. Updating can considerably improve the accuracy of forecasts, although towards the maximum lead time of the forecast the influence of the observed flows will often decay offering little improvement at these lead times.

The following discussion considers the following three main aspects of model performance:

- Sensitivity to the spatial and temporal averaging of rainfall
- Relative performance of models (i.e. all using the same input data; good or bad)
- Propagation of errors in input data into model outputs

a) Spatial and temporal averaging effects

Most (if not all) rainfall runoff models at some point require some spatial averaging of the input rainfall data in order to operate. This might consist of deriving an area average value from raingauge data, or using spatially averaged outputs from weather radar.

An important factor to be aware of is that spatial averaging will tend to reduce the peak rainfall intensity which is recorded which can have a major impact on forecast values for peak river levels and flows. This effect arises from the non linearity of the rainfall runoff process; for example, intense rainfall falling on part of a catchment may generate much higher runoff than lower intensity rainfall which may be absorbed by the soil or infiltrate to groundwater. Distributed rainfall runoff models should therefore use the highest resolution data available as input to the model.

These effects are sometimes referred to as storm smearing and watershed smearing (Ogden and Julien, 1994; World Meteorological Organisation, 2000). Storm smearing occurs when the rainfall data (grid) length approaches or exceeds the rainfall correlation length (which is only about 2km for thunderstorms). This tends to decrease rainfall rates in high intensity regions and increase rainfall rates adjacent to low intensity regions thereby tending to reduce rainfall gradients. This effect is independent of catchment size. Watershed smearing occurs when the radar grid size approaches the catchment characteristic size (which depends roughly on the square root of the catchment area). In this case the uncertainty regarding the location of the rainfall within the catchment boundary is increased. Hence in convective rainfall in which large rainfall gradients are present it is necessary to use a radar grid size of around 1km in order to obtain accurate estimates of peak flows. However, 2km or even 5km grid lengths are adequate for larger urban and rural catchments.

b) Relative performance of models

Most studies of model performance tend to focus on the relative performance of models and ignore any possible problems in the input data. However, there have been relatively few quantitative intercomparison studies. In part, this is because of the difficulty of performing this type of intercomparison; for example Reed (1984) suggests that a thorough assessment of rainfall runoff methods for flood forecasting might need to consider:

- At least four distinct approaches (e.g. unit hydrograph, ISO, transfer function and conceptual models)
- Perhaps four different model structures in each approach (e.g. several methods of rainfall separation in the unit hydrograph approach)
- Several methods of real time correction (e.g. error prediction, state updating or parameter updating)
- Perhaps several types of rainfall forecast (e.g. none, qualitative, quantitative, perfect foresight)
- Various objective functions both for model calibration and performance assessment
- Application to a range of flood forecasting problems (perhaps six catchments)

To this list might be added the uncertainties introduced by the skills of the people implementing the models and those responsible for calibrating them. Table 1.5 summarises some typical results from recent intercomparison and review studies.

Table 1.5. Summary of conclusions from recent rainfall runoff model intercomparison studies/reviews

Source	Description of study and results
World Meteorological Organisation, 1992	The third such intercomparison exercise sponsored by WMO involving 14 models from 11 countries (previous studies were in 1974 and 1983). Models were compared using data for catchments with areas of 104, 1100 and 2344 sq. km with updating including using statistics such as rmse and graphical comparisons. The report simply presents results for further analysis and does not discuss optimum models for different situations or typical model accuracy's.
National Rivers Authority, 1993	This was an intercomparison study for 9 catchments in Thames Region for 30 storm events up to 1992 using different complexities of conceptual model (PDM, TCM, IEM). Best performance was obtained on small to medium impermeable catchments and worst on large groundwater dominated catchments. No one model was consistently best and peak flow errors were more influenced by rainfall estimates than the choice of model. Updating provided a significant improvement which decreases with increasing lead time, with state correction working best when errors were due to soil moisture accounting. Shorter period updating (e.g. 15 minute) worked best at short lead times and for fast response catchments
National Rivers Authority, 1995a	This general review of previous studies concluded that conceptual models perform better on large catchments, at long lead times, but that most models have similar performance at short lead times and for small catchments. The root mean square error in model output roughly doubles for each 3 hours of lead time. Studies into the operational advantages of fully distributed models were recommended
Environment Agency, 1998c	Simple empirical statistical models generally provide less good, or more general forecasts, than transfer function models or conceptual models for lead times greater than one hour. For shorter lead times the accuracy of the approaches may not differ substantially. There is little difference between transfer function models and conceptual models for short and medium lead times. Conceptual models may give better forecasts over longer lead times. In most circumstances distributed or semi-distributed models offer little advantage over lumped catchment models. Lumped models are invariably cheaper and are therefore taken to be the most complex best practice solution for all but exceptional circumstances. The circumstances in which a distributed model or a semi-distributed model is best practice are where rainfall input error does not dominate over model error (i.e. where the spatial structure of the rainfall input is well measured, and where the subcatchment size is much greater than the size of rain producing storm). On complex urban catchments, highly varied urban land use and artificial drainage networks can behave inconsistently and be difficult to accommodate in a model. In some cases simpler models can perform acceptably but elsewhere a semi-distributed approach may be required to account for the variation on land surface and the drainage network may require explicit modelling. This may be achievable but it is not well proven. Such methods would also require a highly accurate spatial description of the rainfall field. These problems are a field of current research which has had mixed results. An operational system using such techniques is unlikely to be realisable at present
Environment Agency, 2000c	This remains the most comprehensive rainfall-runoff model intercomparison commissioned by the Agency to date involving comparisons of several operational and

	research models on eight catchments in England and Wales. The following recommendations were made, where a simple model might be the IEM model, a linear transfer function model, or a lumped conceptual model (although note that the use of non linear and parallel pathway transfer function models was not considered in detail and further studies are proposed; see Part C): **Small Catchments** Upland impervious, rural or urban - use simple models Urban clay – simple lumped models may be acceptable but zoned or semi distributed conceptual models may perform better **Medium Catchment** High relief impervious – Most models perform well including simple models High relief mixed geology – Conceptual models recommended Lowland permeable (chalk) – Groundwater dominated – Conceptual models with further development to incorporate real time borehole level data and pumped abstractions etc Modest relief, rural – good performance can be obtained from simpler models Modest relief, significant urban – responsive so as above (although semi distributed models can help) **Large Catchments** Lowland clay – Conceptual models recommended Lowland chalk – Conceptual models with further development to incorporate real time borehole level data and pumped abstractions etc Most of these studies were performed using raingauge data but locally adjusted radar data was used for a parallel set of tests on three catchments and was found to provide comparable or better results than raingauges on two of these catchments (although this aspect of the study was hampered by radar data issues for the calibration period selected)

Figure 1.3 summarises the results from the last entry in the above table (Environment Agency, 2000c) in terms of the variation in CSI scores with lead time for the 4 fast response catchments and 4 slower response catchments with model updating. It can be seen that, for the best performing models, similar scores are obtained whilst the worst performing models do considerably worse on the larger slow response catchments. For the best models (i.e most appropriate), the general trend is for the CSI to drop to about 80% after 1-2 hours, and then to reach about 60% after 6 hours.

Of course the CSI is only one measure of model performance and similar trends are seen for the R^2 statistic, although this is a less sensitive indicator of model performance, with most models giving values of 0.9-0.95 at a lead time of 6 hours for the best models, and the poorest score on any catchment for the best model being about 0.75. These results all apply to the models using forecast updating based on observed flows and R^2 values were typically improved by 0.2 or more by applying updating (compared to simulation mode). Updating is therefore a crucial aspect in successful flow predictions using rainfall runoff models.

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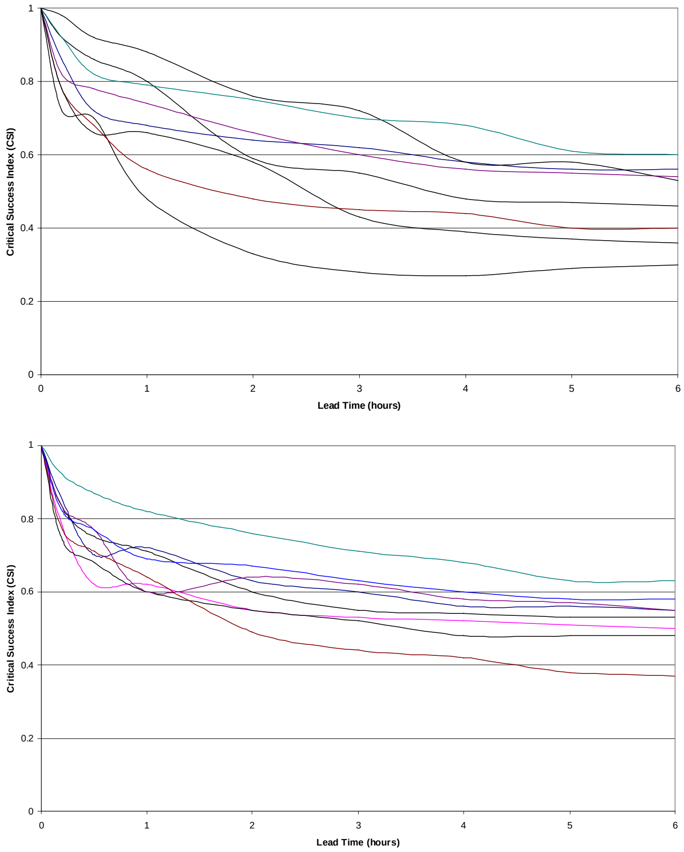


Figure 1.3. Summary of results from project W242 (Environment Agency, 2000c) (top figure 4 large slow response catchments, lower figure 4 fast response catchments)

c) Propagation of errors

There have been comparatively few studies of the impacts of input data errors on model output since most studies assume perfect knowledge or foresight of rainfall (whilst usually acknowledging that there are likely to be errors in the data).

Table 1.6 summarises some example results on error propagation in rainfall runoff models, where the aim is to give a flavour of academic and other research in this area.

Table 1.6. Summary of conclusions from studies of error propagation in rainfall runoff models

Source	Description of study and results
Collier and Knowles, 1986	An ISO-type model was calibrated for the rivers Ribble, Darwen and Wyre (1053, 274, 40 sq.km.) in North West Region using locally adjusted radar rainfall actuals. Results are also reported for the Dee in Wales. Errors in flow predictions were estimated in real time by comparisons with raingauge data alone. For most of the events analysed the relationship between rainfall errors and peak flow errors was approximately linear for small catchments, but roughly a third for the largest catchments when the rainfall was overestimated, and linear for underestimation. However, no general rules could be discerned (with more analyses for more catchments recommended) and the results were model specific
Storm *et al.*, 1989	This study examined the influence in estimated errors in areal rainfall on runoff using the NAM conceptual model for a small catchment in Denmark over a two year period. The studies were performed using daily data and showed a general trend for the uncertainty in runoff (as a standard error) to be 40% or less of that in rainfall i.e. the model damped the perceived uncertainties in rainfall, particularly during the summer months when the runoff was low.
Michaud and Sorooshian, 1994	A review showed that there is no general agreement on the impact of rainfall errors on runoff with some studies showing little effect and others ranging from zero to more than 100% in flood peaks. Three rainfall estimation schemes were examined for a 150 sq.km. experimental catchment in a semi arid region (Arizona, USA) using a typical operational raingauge density, a dense network, and 4x4 km averages (simulating radar) and a semi distributed conceptual model. For 10 convective storms, the 4x4 km averages reduced peak flows by about 50% on average (consistent underprediction), whilst inadequate raingauge sampling caused a reduction of 58% (more random), with roughly half of these latter errors attributed to the rainfall runoff model parameterisations, in particular for infiltration. A 2x2 km radar resolution or better was tentatively suggested for 50-500 sq.km. catchments in semi-arid areas.
Obled and Datin, 1997	A review of flood forecasting practice in mountainous regions in France including some issues related to the propagation of rainfall errors in flow forecasts. For example, Monte Carlo simulations were used to generate plausible error scenarios related to raingauge operational status, accuracy and areal averaging techniques, and used to place 90% confidence limits on rainfall for selected storms, and then routed through a rainfall runoff model (giving a roughly linear translation of confidence limits). Inclusion of model parameterisation uncertainty was not considered although recommended for future studies.
Singh, V.P., 1997	A general review article on the impact of spatial and temporal variability in rainfall and catchment characteristics on flows estimated by rainfall runoff models, including the impact on flood peaks of a) storm speed and direction of travel relative to the main river b) storm size and shape relative to the catchment c) spatial variations in rainfall d) storm duration and profile e) processes and scale in the rainfall runoff model, and other factors, although not leading to any definitive general guidelines
Sun *et al.*, 2000	Flood hydrographs for the Finniss river in Darwin, Australia were estimated using alternate methods for area averaging/processing raingauge and radar data, and a simple semi distributed non linear (ISO type) rainfall runoff model without updating. For an 80 sq.km. subcatchment with a dense raingauge network, errors for the different areal averaging methods were assessed to be 22, 20 and 13% but to cause errors of 32, 26 and 41% in peak flows.
Young and Thomlin, 2000	This review of non linear transfer function modelling included a case study of the impact of the errors caused by using different rainfall estimation methods in a non linear parallel pathway transfer function model applied to the River Ribble catchment in North West Region. In terms of the four hours ahead R^2 coefficient, best results were obtained using raingauge data or locally calibrated radar data, with some variability between sites in the effect of the different rainfall area averaging procedures used

From the above examples, and other reviews performed as part of this study, the following research themes emerge regarding the impact of rainfall errors on flow forecasts (although as yet with few general conclusions suitable for operational use, and mainly applicable to simulation mode):

- Stochastic and other sampling of radar rainfall fields to assess runoff sensitivity to spatial and temporal sampling errors and storm scale relative to catchment scale (e.g. Ogden and Julien, 1994, Sun *et al.*, 2000)
- Statistical and 'pattern recognition' methods for predicting rainfall arrival processes and impacts on flows e.g. depth/duration/intensity/clustering/autocorrelation (e.g. Obled and Datin, 1997; Wheater *et al.*, 2000)
- Intercomparisons of the impacts of using different rainfall actuals in rainfall runoff models (e.g. different area averaging methods for raingauges, different local adjustment techniques for radar) (e.g. Young and Thomlin, 2000; Sun *et al.*, 2000)
- Predicting the impact of tracking (speed/direction) and development/decay errors for individual storms (e.g. Mecklenburg *et al.*, 2001; Ebert and McBride, 2000)
- Purely statistical sampling in which assumed autoregressive, bias and other errors are propagated through rainfall runoff models (see Troutman, 1983 for a general review)

1.5.3 Routing Models

Errors in routing models can arise from the model structure, the model calibration, accuracy of survey data (in hydrodynamic models), ungauged inflows, representations of hydraulic structures, the downstream boundary conditions and other factors. If, as is usual, computations are performed in terms of flows, then a rating equation will be needed to convert flows at the forecasting point(s) to the levels which are required for issuing flood warnings.

The classical flow routing problem consists of a single river reach with no significant tributary inflows and no structures, out of bank (floodplain) or other flows. In this case, provided that suitable calibration data are available, excellent results (peaks to within a few percent) can be obtained from most types of routing model, particularly when using real time updating of flows. Level and flow correlations can also be used in this situation if only peak values are required.

To discuss the accuracy of routing models in more complex situations, it is convenient to make a distinction between hydrodynamic models and those simpler types of model (e.g. Muskingum, Kinematic Wave) which make additional approximations to the St Venant equations:

a) Hydrodynamic models

For hydrodynamic models, review studies of performance in simulation mode suggest that that the following indicative accuracies should be achievable with a properly calibrated model used in appropriate flow situation under UK conditions (e.g. Samuels, 1995; Environment Agency, 1997; Ramsbottom *et al.*, 2000):

- Topographic errors – errors in levels of 0.1-0.3 m
- Section spacing errors – typically within 0.01m
- Model calibration issues – error in levels of 0.15 m within the range of calibration (more outside)
- Rating equation uncertainty at high flows – error in levels of 0.2-0.5 m
- Additive errors – up to 0.75 m (assuming all other errors statistically independent)

These estimates are based on a review of numerical modelling studies performed in the USA and UK using idealised river configurations and coarsening the grid resolution in 1D models, or assuming plausible errors in the survey and other data. These results apply to simulation mode and may be significantly reduced in updating mode, although little work appears to have been done on this topic. However, the uncertainty in the high flow end of rating equations is clearly of major importance and is the subject of R&D project "Extension of rating curves at gauging stations W6/060" which reports in 2003.

A project "Reducing uncertainty in river flood conveyance" is currently addressing the whole issue of selection of model parameters such as channel roughness, and assessment of uncertainty in conveyance, in UK rivers and is being implemented over the period 2001-06 (with the first phase reporting in 2004).

For simulation modelling studies (for example flood risk modelling), the default accuracy targets for river models are:

- The accuracy shall generally be +/-0.25m on the 100 year water level (or, in tidally influenced reaches, the 200 year water level)
- The accuracy of the river model is to be such that for at least three calibration events (covering both in bank and out of bank flows) the mean error plus one standard deviation of the error at all stations and over the whole time span of the events shall not exceed 0.15m

These values refer to a given return period and are target values (and a model will not be assumed to be unacceptable if it fails to meet these values providing that the reasons for failure and actual accuracy are clearly stated).

In real time operation, models may be simplified (for reasons of stability or run time) but, on the other hand, real time updating may be used to improve forecasts. However, there does not appear to have been any in depth study of the accuracy and optimum updating approaches for hydrodynamic models under the conditions typical of UK rivers.

b) Simpler routing models

Models which fall within this category include:

- Muskingum
- Extended Muskingum (e.g. DODO)
- Muskingum Cunge
- Kinematic Wave
- Variable Parameter Muskingum Cunge
- Extended (or variable parameter) Kinematic Wave
- Variable Parameter Diffusion

Much of the theoretical work for this type of model was established in the 1960s and 1970s by Cunge (1969), Price (1973, 1977) and others although research continues today, particularly into the performance of the variable parameter versions.

For example, the UK Flood Studies Report of the mid-1970s recommended the following strategy for selecting an appropriate routing model:

1) Assess the reach characteristics (travel times, inundation of the floodplain etc)
2) Assess attenuation of the flood wave (from data or theory)
3) If the attenuation is more than 10% use variable parameter routing provided that the data can support it (i.e. wavespeed-discharge and attenuation-discharge curves can be defined)
4) Otherwise use fixed parameter versions (e.g. Muskingum Cunge)

The following table summarises the recommendations of a number of other key review and research studies into the performance of routing models.

Table 1.7. Summary of conclusions from studies into the accuracy of routing models

Type of model	Recommendations and results
Price, 1973	Three case studies (Wye, Nene, Eden) using the Muskingum Cunge and variable parameter diffusion models led to the following conclusions: • Peak discharge errors were in the range 0-12% (but 21% on the Nene due to structures) • Time of travel errors were in the range 1-10% (20% on the Nene) • Mean flow/volume errors were all in the range 10-20% (Wye – 70km reach, extensive floodplain, slope of 0.0009 Eden – 38km reach, slope of 0.0016, little attenuation Nene – many control structures/high retention levels, floodplain) Intercomparisons on an idealised rectangular river channel, typical of UK rivers, showed the characteristic behaviour of the simpler routing methods for in bank flows i.e. the peak is predicted well but, due to the assumption of fixed wave speed, there are considerable errors at low flows for fixed parameter methods (although the Muskingum Cunge approach by definition conserves volume).
National Rivers Authority, 1995a	Hydrodynamic models are required where there is upstream movement of waves such as tidal action or storm surges, backwater effects caused by downstream reservoirs and tributary inflows, $s<<0.005$, 'waves' due to rapid reservoir releases or abrupt changes in velocity (e.g. regulation). The diffusion approach can model backwater but not tidal effects. The fixed parameter kinematic wave approach cannot model backwater or channels with slopes below about 0.001
Environment Agency, 1998c	There is no general agreement on the best modelling tools. However the following general observations apply: • Simplifications to the St Venant equations cannot represent the upstream movement of waves such as tidal action or storm surges, or abrupt waves or changes in velocity, for example caused by sluice gates or reservoir release • Backwater effects typically occur on rivers with extremely flat bottom slopes (much less than 0.005) • The diffusive wave approximation can handle backwater but not tidal or wave effects. • The kinematic wave approach (fixed parameters) is satisfactory where there are no significant backwater effects and slopes are greater than around 0.001 • Hydrological routing is as good as hydrodynamic modelling where the accuracy is dominated by uncertainty in lateral inflows to a reach rather than the modelling of flows in the reach.
Tang *et al*, 1999a, and b	A series of numerical experiments (MAFF funded) were performed using different formulations of the VPMC method for different bed slopes and space/time steps, showing that traditional formulations can have volume losses of up to 10% for a flood event on flat rivers (slope of 0.0001-0.001), with a classical 'leading edge dip' at the start of the flood hydrograph and instabilities on the recession limb in compound channels (i.e. floodplains) for slopes > 0.003. These arise from the choice of representative discharge in wave speed and other parameterisations (e.g. space/time steps, 3 point vs 4 point schemes etc). A new formulation is proposed which greatly reduces these problems.

1.6 Performance of Operational Systems in the Agency

As one of the key components of a flood warning system, Real Time Models have a significant influence on the Accuracy, Reliability and Timeliness of the overall system; the other main component being the effectiveness of the warning dissemination systems (and the public's response to those warnings).

However, with only a few exceptions (see later), most studies of model performance within the Agency and the former National Rivers Authority have tended to be both site and model specific, and to some extent to depend on local operational procedures.

The aim of this section is to review some recent studies of overall performance at the Regional and National level, and to indicate the implications for the recommendations made in the guideline documents.

1.6.1 R&D Technical Report W17

This study (Environment Agency, 1996) aimed to review the overall effectiveness of the Agency's integrated flood forecasting systems under operational conditions, and followed on from a similar study in 1991 and 1992. Here, an integrated system was defined as one that provides automated forecasts of flows, rather than the at-site triggers and manual procedures used in some Regions.

The systems which were reviewed included those used in the then Northumbrian & Yorkshire and Severn Trent Regions, and Thames, North West and South West Regions. The report drew attention to the need to further develop these systems and to evaluate their performance in operational use using automated evaluation procedures, and a number of suggested performance measures were suggested. That is, post event analysis (or monitoring and evaluation) was identified as one of the keys steps towards improving model performance in future.

The main performance statistics reported were for Severn Trent (now Midlands) Region, which showed that model forecasts played a major role in issuing flood warnings and that on average warnings were issued some 2.5 hours ahead of flooding, with a Reliability in the range 75-95%. A histogram presentation for minimum warning time was used which has been adapted for use in the guideline document (see Figure 1.4).

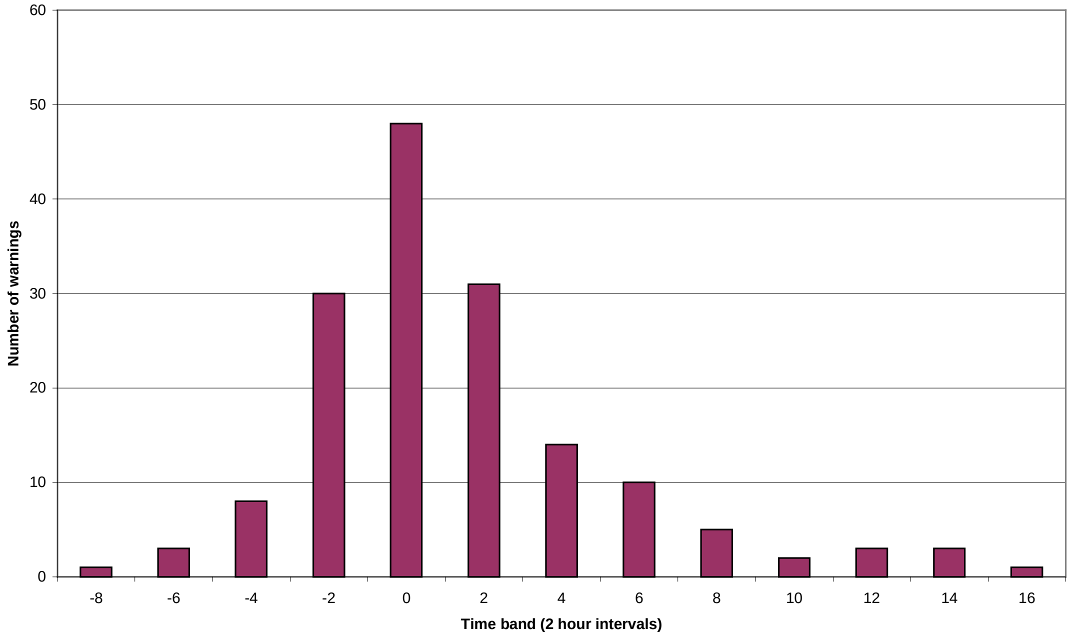


Figure 1.4. Example of summary results for the Timeliness of Flood Warnings (or Severe Flood Warnings) at a site (or sites) over several flood events (hypothetical data)

To assist with future evaluations of performance, a method for estimating forecast lead times was proposed based on various time delays in the forecasting and warning process, and this forms the basis of the method outlined in Part A of this report (as later improved by Midlands Region and by this project). A form of Critical Success Index was also suggested as a way of monitoring the success rate in issuing flood warnings. Regarding evaluation of warning times, the point was made that it is important to monitor system performance at the minimum warning time required by users of the information (e.g. the public, Agency staff etc) although no attempt was made to define what these times might be.

1.6.2 Midlands Region Level of Service

Following on from the above report, Midlands Region developed the suggested performance evaluation procedures further using a regional database of some 800 flood warnings for the period 1992-96 (Environment Agency, 1998d).

A distinction was made between the 'front end' of the process (i.e. all aspects up to the time at which the warning is issued) and the 'back end' (i.e. all actions following the warning). The two key performance measures used were the Timeliness of warnings, and a parameter defined by National Flood Warning Output and Performance Measure OPM1 as the:

Number of people receiving a flood warning and flooded / Number of properties flooded

This parameter was called the "Accuracy" in the report (and is an earlier version of the term Reliability defined in the National Flood Warning Investment Strategy; see Part A). The definition of Timeliness at that time was:

"A prior warning will be provided (2 hours in general) to people living in designated flood risk areas where a flood forecasting facility exists and where lead times enable us to do so"

A separate parameter, also called Reliability, was introduced in which a flood warning is considered to be Reliable if:

- All appropriate elements are in place (dissemination methods, plans, leaflets etc)
- All elements are considered to be functioning satisfactorily
- It is considered to be the most appropriate method for the river reach

(although note that this is different to the term "Reliability" as used in this report).

The key improvement made in this study was to recognise that, in order to estimate Timeliness, the data used need to be readily available from the operational system. The two main events used were the time at which a warning is issued, and the time at which a trigger level was crossed, from which minimum warning times can be estimated and summarised by river reach as indicated in Table 1.8.

Table 1.8. Suggested format for summarising forecast warning time performance (adapted from a format used in Midlands Region; all values hypothetical).

Reach and type of warning		**Minimum warning time achieved**						
		After start of flood	**< 2 hours**	**2-4 hours**	**4-6 hours**	**6+ hours**	**Modal value (hours)**	**Target (hours)**
A1	SFW	0	0	0	0	0	-	2
Lilbourne	FW	1	7	**4**	0	0	< 2	
A2	SFW	0	0	0	0	0	-	2
Rugby	FW	1	0	0	0	0	After	
A3	SFW	0	0	0	0	0	-	2
Warwick	FW	1	0	0	0	0	After	
A4	SFW	0	0	**2**	0	0	2-4	2
Stratford	FW	0	1	**3**	1	0	2-4	

SFW = Severe Flood Warning
FW = Flood Warning

This hypothetical example shows a mixed performance, with some sites meeting national minimum warning time targets (on average) and others failing to meet targets (although possibly only by a small margin)

The method used for estimating the success of forecasts was a form of Critical Success Index (CSI). At that time, the old yellow, amber and red warnings were still in place, so the following table shows an updated version of the method (using hypothetical data):

Table 1.9. Suggested format for summarising forecast warning time performance (adapted from a format used in Midlands Region; all values hypothetical).

		Observed level			**Overall performance**	
Reach	**Type of warning**	**Severe Flood Warning (SFW)**	**Flood Warning (FW)**	**No warning (None)**	**Total number of warnings**	**Critical Success Index**
A1 Lilbourne	SFW	0	0	0	0	0.57
	FW	1	**8**	3	12	
	None	0	2	-	-	
A2 Rugby	SFW	0	0	0	0	0.25
	FW	0	**1**	0	1	
	None	0	3	-	-	
A3 Warwick	SFW	**1**	0	0	1	0.67
	FW	0	**1**	1	2	
	None	0	0	-	-	
A4 Stratford	SFW	0	0	0	0	1.00
	FW	0	2	0	2	
	None	0	0	-	-	

SFW = Severe Flood Warning
FW = Flood Warning

These tables are recommended in the guidelines as one of the post event analysis techniques which could be used nationally (if required).

1.6.3 EA Wales Approach

The Midlands approach provides one way of estimating whether national performance targets are being met at a site or Regionally. However, for situations where a rapid appraisal is required, or the supporting data are not available, a more qualitative approach may be useful as a start.

Following the Easter 1998 floods, EA Wales developed a rapid appraisal procedure to help to prioritise the installation of new gauging stations and raingauges to support flood warning. This was performed as part of a Hydrometric Improvements Project.

For each site, a score was assigned based on operational experience over several significant events and the results were then tabulated by site. The scoring system used was:

Reliability:

1) Reliability exceeds national target of providing 80% or more of properties in receipt of a four stage warning service with warnings in sufficient time to take action
2) Requires minor improvements to models and/or instrumentation (Reliability 40-80%)
3) Requires major improvements to models and/or instrumentation (Reliability < 40%)

Timeliness:

1) 2 hours or greater i.e. possible to issue warnings meeting the Customer Charter commitment

2) Less then 2 hours i.e. not presently possible to issue warnings to meet the Customer Charter commitment

A GIS presentation of this type of information has proved useful for identifying specific catchments where performance improvements were needed and spatial trends in performance within the catchment (e.g. specific Flood Warning Areas with performance issues, or problems with achieving sufficient minimum warning times in the headwaters of fast response catchments). The following example is for the Taff catchment.

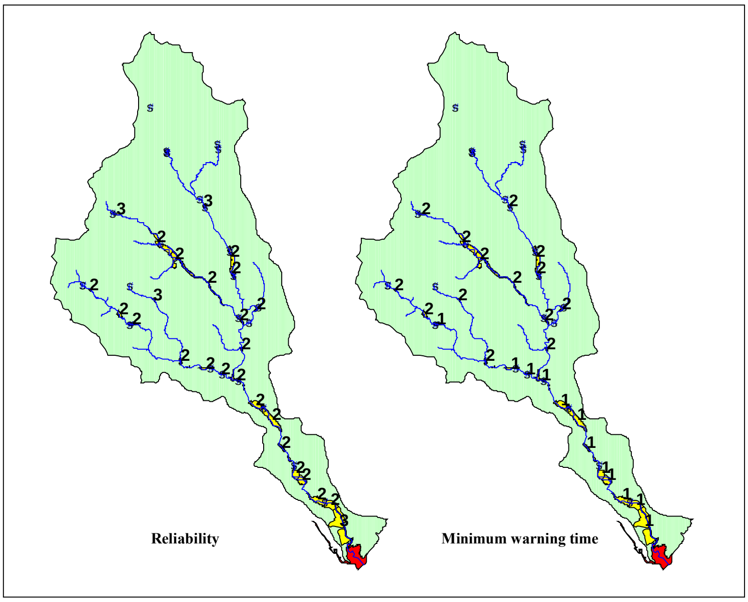


Figure 1.5. Pre-hydrometric improvement scores for Reliability and Timeliness (now superseded)

1.6.4 North East Region Forecasts Improvements Project

Another approach to post event analysis is currently being developed by North East Region (2000-on) as part of a project to evaluate and recalibrate (if necessary) the Real Time Models built into the Regional Flow Forecasting System (RFFS). Initial assessments were based on the ability to predict the timing and magnitude of the flood peak, but have subsequently been extended to assess success at forecasting threshold exceedances (e.g. trigger levels).

In the methodology, the following information is tabulated for each flood event:

- Observed peak level and time
- Time of crossing of the threshold level

together with the following information for each forecasting run within the event:

- Lead time to observed peak
- Timing error in peak
- Magnitude error in peak

and

- Lead time to observed threshold exceedance
- Timing error in threshold exceedance

Values are then plotted using the presentation technique indicated earlier in Figure 1.1(a) and illustrated in the following example for a high flow event in Wakefield in October 2000.

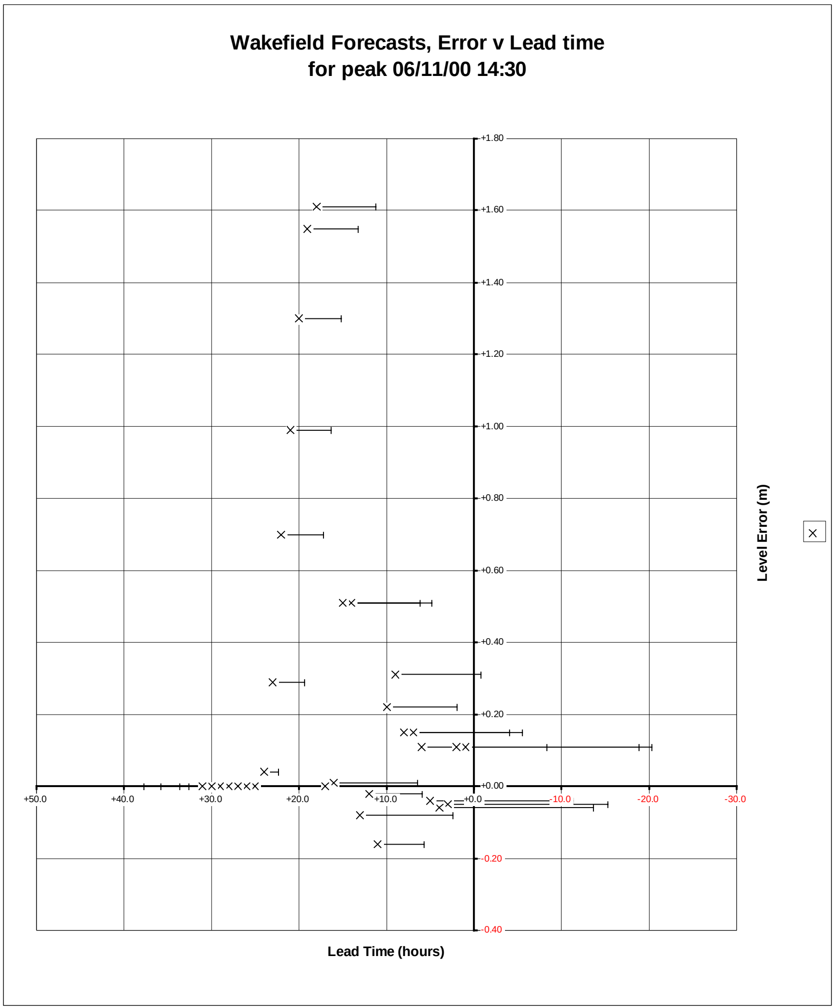


Figure 1.6. Example of the North East Region approach to forecasting system evaluation

Figure 1.7 shows an alternative presentation which might be used, focussing on how the errors vary in the run up to the peak. In the example shown, the timing and level errors were surprisingly small at long lead times, but became much larger in the few hours running up to the event.

Having evaluated performance for single events, results are then aggregated using a CSI-type approach, in which individual forecast points are scored using the following matrix, with the focus on the performance of predicting flood peaks. The following ranking scheme is used with the weights assigned to peak level forecasting are twice those of the peak time forecasting assessment.

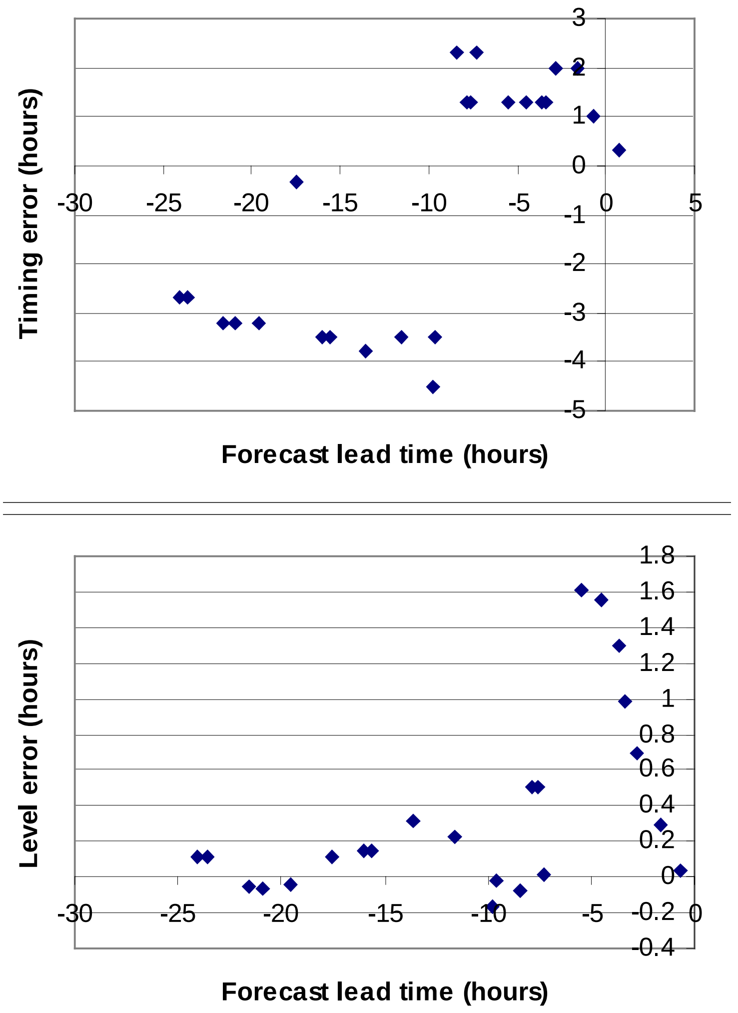


Figure 1.7. Example of level and timing errors for the 6 Nov 2000 high flow event at Wakefield (illustrative only)

Table 1.10. Example of a Forecast Performance Assessment Matrix for North East Region

Peak Level Forecast	good	6	7	8	9
	medium	4	5	6	7
	poor	2	3	4	5
			1	2	3
			poor	medium	good
			Peak Time Forecast		

1.7 Post Event Analysis Techniques

One of the objectives of the present project was to review and evaluate techniques for post event evaluation with a view to making a start towards establishing some standard approaches within the Agency. This section aims to bring together a selection of methods which might be used based on the reviews in the preceeding sections, and methods evaluated as part of the exploratory modelling studies (see later). Although this results in some repetition of text presented elsewhere, it is convenient to place these 'best practice' recommendations in a single location for easy reference (and note that a similar section appears in the guidelines on "Rainfall Measurement and Forecasting" guidelines concerning the post event analysis of meteorological data).

The following post event reporting strategies are therefore recommended for the three main requirements of:

- Post Event Reporting following large flood events
- Assessing Regional compliance with High Level Targets
- Long term monitoring and evaluation of model performance

and any, or all, of these measures can be used as required depending on Regional requirements. Note that, with the exception of the high level targets of Timeliness and Reliability, all other measures presented here relate to model Accuracy (which is not formally a target at present).

1.7.1 Post Event Reporting

In post event reporting, the focus is usually on the performance of the flood forecasting system for specific sites at which flooding occurred using data and forecasts archived during an event. This might also include studies into alternative scenarios which might have occurred during an event (for example "if we had opened the washland gates two hours earlier what would have happened….") although this topic is not considered here.

a) Success at forecasting the hydrograph

For assessments of Accuracy alone, the most common requirement is to record model performance statistics regarding predictions of the peak flow for different lead times. For models which only predict peak flows (e.g. correlation models) then a simple table showing the time and magnitude of the observed peak, and the corresponding values for the forecast, should be sufficient.

For models which forecast the whole hydrograph, then fixed lead time assessments are extremely useful, and are provided as standard output in many Real Time Models. Here, the fixed lead time values are those obtained for each time step in the model run at a given lead time (e.g. 1 hour, 2 hours ahead etc). By interpolating between these values, a pseudo hydrograph can be constructed for comparison with the observed values, from which the magnitudes of the peak level or flow at different lead times can be tabulated for comparison with the observed value.

Graphical comparisons can also be useful and Figure 1.8 shows an example of a fixed lead time comparison in which the longer lead time forecasts of the peak were consistently too high in the early part of the event, but the short lead time forecasts performed well throughout the event.

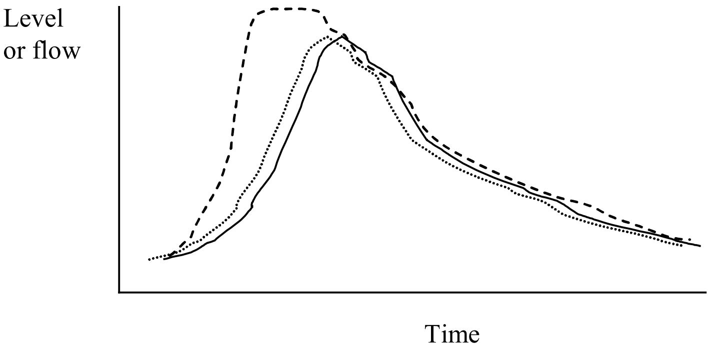


Figure 1.8 *Example of a fixed lead time forecast comparison (solid line-observed values, short dashes-short lead time, long dashes-long lead time)*

For this type of comparison, it is also useful to estimate the following statistic for each fixed lead time for input to longer term assessments of model performance (see later):

$$R^2 = 1 - \frac{\sum e^2}{\sum (Q - \overline{Q})^2}$$

where Q is the observed flow, Q_f is the forecast flow, e = Q – Q_f is the difference between observed and forecast flows, an overbar indicates a mean value, and N is the number of time steps over which the statistic is computed. This measure gives an indication of the overall success at forecasting the hydrograph shape/volume and, again, many Real Time Models will compute this statistic automatically.

The optimum value is 1.0 and a value of 0.0 indicates that the model is performing no better than simply assuming the mean flow (negative values are also possible). For an idealised single peak hydrograph with no timing errors, the error in peak flows is given approximately by $\Delta Q/Q \approx \sqrt{(1-R^2)} / 2$ although can be considerably smaller than this if there are timing errors.

b) Success at forecasting the crossing of thresholds

Another approach to summarising performance is to examine the success of the model (or whole forecasting system) in predicting the crossing of threshold levels (or exceeding the corresponding flows). For flood warning, two important threshold values are those at which a Flood Warning and a Severe Flood Warning are issued.

The Critical Success Index provides one way of scoring the success rate in predicting the crossing of thresholds as shown in the following table:

Table 1.11. Example of a flood forecasting Contingency Table

	Threshold exceeded (observed flows)	**Threshold not exceeded (observed flows)**
Threshold exceeded (forecast flows)	A	B
Threshold not exceeded (forecast flows)	C	D

and is given by CSI=A/(A+B+C). A value of 1.0 indicates a perfect forecast whilst the worst value which can be obtained is 0.0.

Normally, this measure would be computed either for one site across many events (see later), or for many sites in the same event, in which case the CSI would be computed by summing the entries for A, B, and C for all sites to give an overall success score for the event.

If evaluating model performance alone, then the values of A, B and C can be based on fixed lead time forecasts, so that CSI is a function of the lead time. Also, if a timing component is to be included, a successful forecast can be defined as one which crosses the threshold with a given time of the observed flows (e.g. 1 hour). If evaluating performance of the whole system (including dissemination), then the CSI can be computed for each site based on whether warnings were issued, and whether flooding occurred or not (and to what degree e.g. “carpets wet”).

1.7.2 High Level Targets

The two main High Level Targets relevant to Real Time Modelling are Reliability and Timeliness. Both are measures of the performance of the whole system (including dissemination) and not just the Real Time Modelling component. However, if warnings are based on model forecasts, then these statistics provide a partial indication of model performance. Studies of compliance with targets can indicate the overall performance of a system by catchment, Region etc and can indicate locations where improvements to instrumentation, Real Time Models, operational procedures etc may be required.

Regarding Reliability, under the current national definition, there is no way to estimate this parameter other than by commissioning post event surveys of property owners in a Flood Warning Area so this will not be discussed further. However, the Critical Success Index shown above provides a related measure, and is the success at forecasting the crossing of a flood defence or other threshold (e.g. trigger levels) and might be used as a crude indicator of Reliability (although differs since Reliability also includes notions of depths reached on the floodplain etc and subjective judgement of what constitutes flooding at a property.

However, the minimum warning time (or “Timeliness”) can be estimated and the following method shows an approach based on the following two key times which are easily extracted from records kept during a flood event:

- T2; the time at which a warning is issued (e.g. as logged in the AVM database, if used)
- T4; the time at which the threshold (e.g. a trigger level) is crossed (which can be obtained from the 15 minute values recorded at the Forecasting Point)

Table 1.12 illustrates how these times relate to other times for a typical Flood Warning scenario.

Table 1.12. Example of a scenario in which a Flood Warning is issued based on forecast levels

Time	Description	Symbol
12:25	The forecasting model first predicts that levels will rise sufficiently to cause flooding at the Flood Warning Area	T1
12:35	Based on flow/level forecasts, 'what if' model runs, and current rainfall and radar images/forecasts, the Flood Warning Duty Officer is notified and decides to issue a Flood Warning	T2
12:55	The AVM dial out process is completed	T3
14:45	The Flood Warning trigger level is exceeded at the Forecasting Point	T4
15:10	The first property floods	T5

In this simple example, assuming the worst case scenario that the last property notified was the first to be flooded, then the minimum warning time achieved is $\Delta T_{warning}$ = T5-T3 = 2 hours 15 minutes, which in terms of the known values T2 and T4 is given by:

$$\Delta T_{warning} = (T4-T2) + \Delta T_{local} - \Delta T_{dial}$$

where:

ΔT_{local} = (T5-T4) = delay between the trigger level being exceeded and the first property being flooded
ΔT_{dial} = (T3-T2) = the time taken to dial out to all properties

and a ΔT symbol indicates a time difference rather than an actual recorded time. Site specific values should be supplied for the two times ΔT_{local} and ΔT_{dial}.

Over time, the minimum warning time values for a site, or a catchment, or a Region, can be accumulated over flood events, and plots such as Figure 1.9 produced to indicate the long term performance of the system:

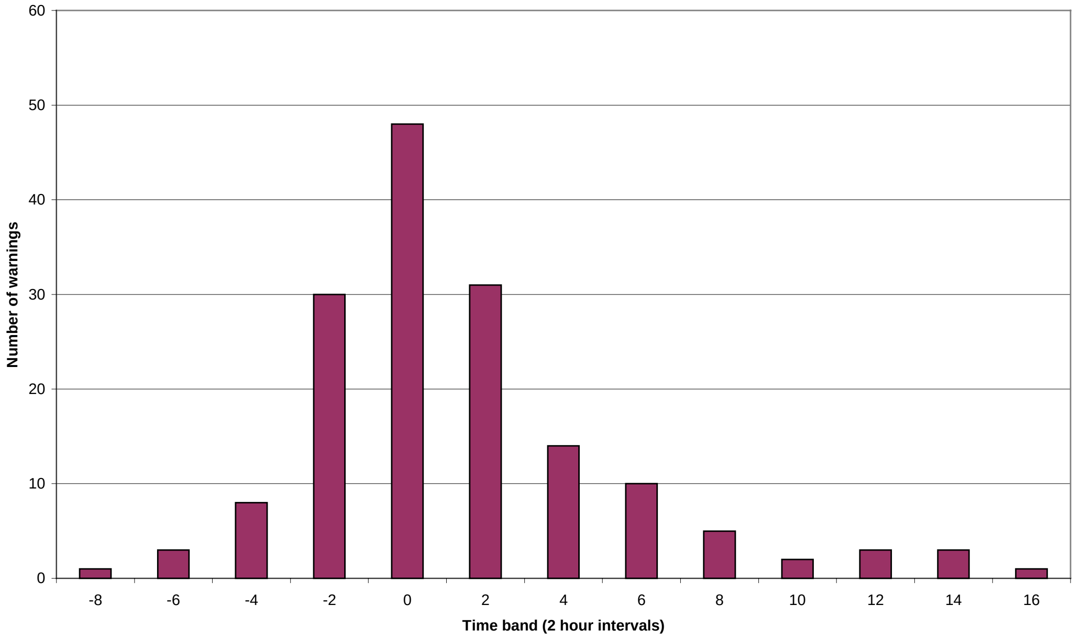


Figure 1.9. Example of summary results for the Timeliness of Flood Warnings (or Severe Flood Warnings) at a site (or sites) over several flood events (hypothetical data)

In this example, minimum warning times are borderline acceptable for meeting the Customer Charter commitment across the Region.

Also, for single sites, tables such as the following can be used to summarise minimum warning time performance across a number of events:

Table 1.13. Suggested format for summarising forecast warning time performance (adapted from a format used in Midlands Region; all values hypothetical).

Reach and type of warning		Minimum warning time achieved						
		After start of flood	**< 2 hours**	**2-4 hours**	**4-6 hours**	**6+ hours**	**Modal value (hours)**	**Target (hours)**
A1	SFW	0	0	0	0	0	-	2
Lilbourne	FW	1	7	4	0	0	< 2	
A2	SFW	0	0	0	0	0	-	2
Rugby	FW	1	0	0	0	0	After	
A3	SFW	0	0	0	0	0	-	2
Warwick	FW	1	0	0	0	0	After	
A4	SFW	0	0	2	0	0	2-4	2
Stratford	FW	0	1	3	1	0	2-4	

SFW = Severe Flood Warning
FW = Flood Warning

This hypothetical example shows a mixed performance, with some sites meeting national minimum warning time targets (on average) and others failing to meet targets (although possibly only by a small margin). A similar table can also be produced using a CSI type approach although it should be remembered that the CSI is only partially related to the national high level target of Reliability.

Table 1.14. Suggested format for summarising forecast warning time performance (adapted from a format used in Midlands Region; all values hypothetical).

		Observed level			Overall performance	
Reach	**Type of warning**	**Severe Flood Warning (SFW)**	**Flood Warning (FW)**	**No warning (None)**	**Total number of warnings**	**Critical Success Index**
A1 Lilbourne	SFW	0	0	0	0	0.57
	FW	1	8	3	12	
	None	0	2	-	-	
A2 Rugby	SFW	0	0	0	0	0.25
	FW	0	1	0	1	
	None	0	3	-	-	
A3 Warwick	SFW	1	0	0	1	0.67
	FW	0	1	1	2	
	None	0	0	-	-	
A4 Stratford	SFW	0	0	0	0	1.00
	FW	0	2	0	2	
	None	0	0	-	-	

SFW = Severe Flood Warning
FW = Flood Warning

For studies of long term performance, a GIS based approach can also be instructive and the following qualitative system, based on an approach used in EA Wales, may be useful. For each site, a score is assigned based on operational experience over several significant events and the results are then tabulated and plotted on a map to examine spatial trends in performance (e.g. specific sites or catchments with problems, or problems with achieving sufficient minimum warning times in the headwaters of fast response catchments):

Reliability:

- Reliability exceeds national target of providing 80% or more of properties in receipt of a four stage warning service with warnings in sufficient time to take action
- Requires minor improvements to models and/or instrumentation (Reliability 40-80%)
- Requires major improvements to models and/or instrumentation (Reliability < 40%)

Timeliness:

- 2 hours or greater i.e. possible to issue warnings meeting the Customer Charter commitment
- Less then 2 hours i.e. not presently possible to issue warnings to meet the Customer Charter commitment

1.7.3 Model Performance

Some questions which post event analyses can help to address regarding model performance include:

- Does the model only perform well in some types of event ?
- How does the model perform outside its range of calibration ?
- Has the model performance deteriorated since it was calibrated ?

The types of analysis required will depend on the type of model and the type of output which it was designed to produce. For example, for a simple model which is not expected to reproduce the full hydrograph, a simple comparison of observed and forecast peak flows at a single location may be sufficient. For a hydrodynamic model, however, comparisons may be required for several Forecasting Points (e.g. river level profiles) at a range of lead times for both peaks and the full hydrograph using a range of performance measures.

Analyses may be across all events for a given model, or may distinguish between storm type (e.g. frontal, convective, location of rainfall in the catchment) and the magnitude of the event. It may also be useful to examine model performance when using different types of input data; for example, radar vs raingauge data. Ideally, analyses will be based on forecasts archived during an event but, if the analysis is performed off line at a later date, then the aim should be to recreate the event conditions as best as possible; for example, to use the same updating methods, data as measured (rather than subsequently cleaned) etc

The research literature on Real Time Models includes many suggested ways of evaluating performance and illustrates how often no single statistic characterises all aspects of the model performance (e.g. with respect to peak flows, volumes, timing etc). Also, most ‘brands’ of Real Time Model will include their own set of performance statistics. However, the following examples are suggested as a starting point.

For evaluating the success at predicting peak levels or flows, in addition to time series plots, X-Y scatter plots, for fixed lead times, provide a good first indication of performance relative to threshold levels, as indicated in Figure 1.10.

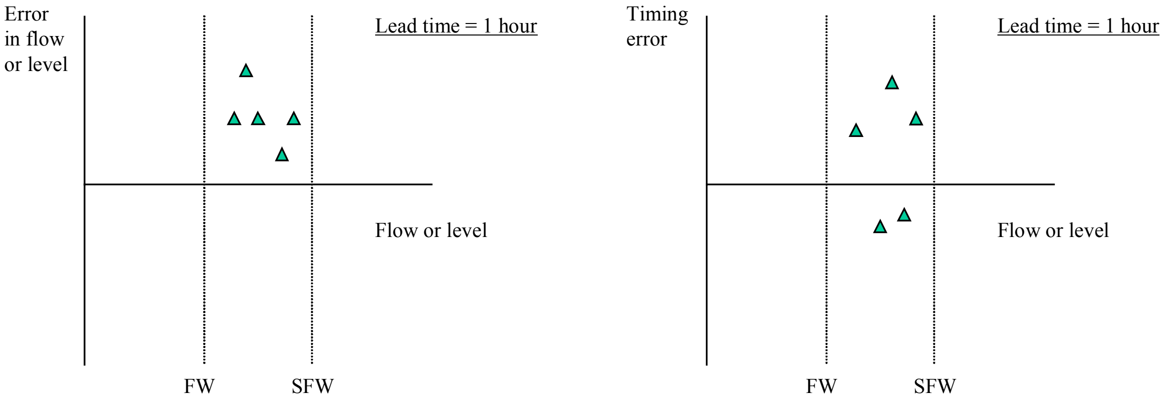


Figure 1.10. Example of peak timing and magnitude error plots for a fixed lead time (FW=Flood Warning, SFW=Severe Flood Warning)

In this simple example, based on 5 events, for lead times of 1 hour, this model consistently over predicts peak values, but has a random error in the timing of the peak. However, the model has not yet been used operationally for levels or flows at which a Severe Flood Warning would be issued. Similar plots might also be used for investigating trends in volume and threshold crossing time errors with flow magnitude.

For intercomparisons between sites or models, it is desirable to present statistical measures in normalised form; for example, to calculate the errors in peak flows as a fraction of the observed peak, and the timing error as a fraction of the catchment time to peak (or lag time in a reach). Also, it is often not meaningful to compare errors in levels between sites due to the different channel characteristics, datums etc used (and so results should not be presented in terms of normalised levels).

Some of the statistical measures presented earlier also allow this type of comparison, so another recommended way of evaluating performance is to plot or tabulate the R^2 and CSI values computed for individual events. The following example shows how the results might appear for a model which has deteriorated over time, particularly for longer lead times (again for 5 events).

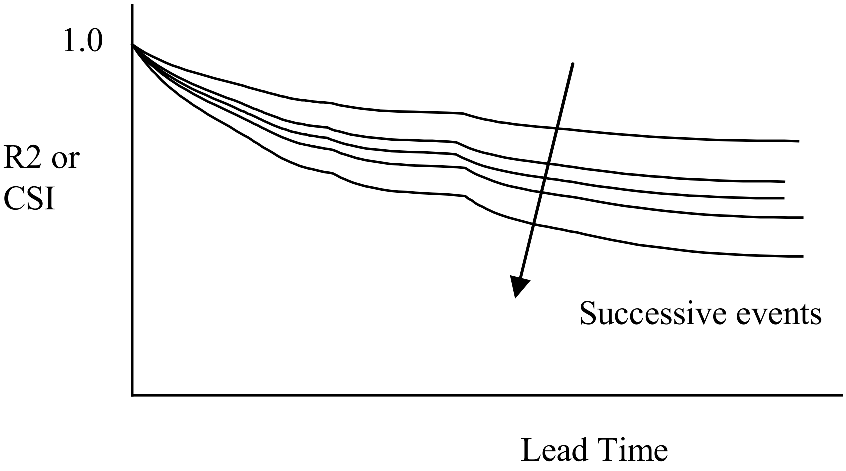


Figure 1.11. Example of plots of model performance over successive events

The CSI values, of course, would need to be quoted with the threshold value used (e.g. Severe Flood Warning). Plots such as these can show a change in model performance over time, prompting further investigations into the need for model recalibration or improvement.

In all descriptions of model performance, it is also useful (if not essential) to provide statements concerning the confidence or uncertainty in model outputs. As a minimum, the standard deviation in estimates across events provides a first guide to the likely spread of errors. The following plot illustrates one possible way of summarising this information for a range of sites, although of course other presentations might be devised along similar lines.

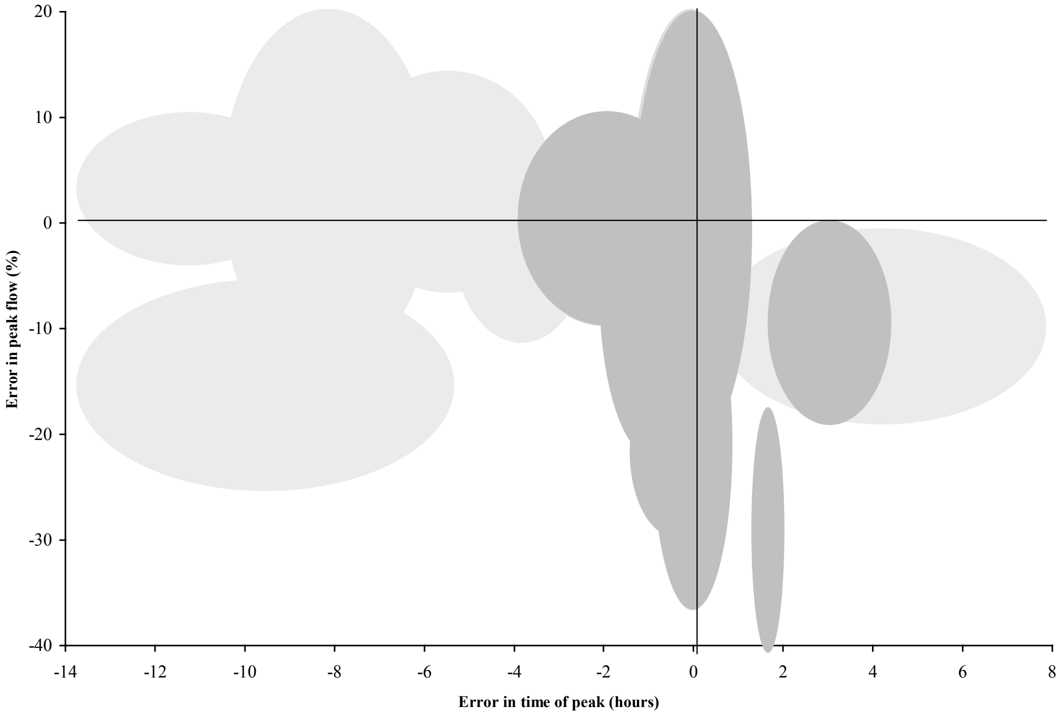


Figure 1.12. Example of one way of presenting information on the variability in model estimates

(bullseye plot or accuracy ellipses)

In the figure, the ellipses are centred on the mean timing and magnitude error in flood peaks, with axis lengths proportional to the standard deviation in errors. Some outlying values where the model performance was unsatisfactory are shown in lighter shading (in this case on certain catchments).

1.8 Methods for assessing forecast uncertainty

The review work and exploratory modelling studies (see later) suggest that the approaches summarised in the following table represent the current ‘state of the art’ in assessing model uncertainty for real time applications. At present, the majority of studies which have been performed within the Agency have been confined to the first of these approaches i.e. sensitivity studies involving adjustments to model parameters.

Table 1.15. Possible approaches to assessing model uncertainty

Approach	**Description**
Assume plausible ranges for parameters/input data	This is the simplest and most common approach to assessing model sensitivity. For a model with many parameters it is important to identify and focus upon those which have most effect on (in this case) flood flows. Both parameters and input data should be varied in a plausible way; for example, for rainfall data, maintaining realistic relationships between event total rainfall and runoff or, for parameter values, assuming realistic ranges and accounting for parameter interdependence. A simple ‘best case/worst case’ analysis may be sufficient in some cases
Stochastic sampling of parameters/data	An improved approach is stochastic sampling either directly from the dataset/assumed parameter sets or indirectly via assumed probability distributions. Some key points are to have a correct representation of extreme events, and not to overlook the effects of parameter interdependence, spatial and temporal correlations in data etc, and again to respect any overall bounds on values. Also, for physically based models, it is important to be aware of aspects of the model which may switch in or out under certain conditions (e.g. fast flow pathways, floodplain flows). Bayesian techniques might also be used to bring in more subjective views of model response. Analytical solutions may also be possible for simpler models using assumed probability distributions for data and/or parameters
Combined stochastic and process-based sampling	A more sophisticated way to assess model uncertainty/accuracy is to combine stochastic and process based descriptions of model response; for example, to consider factors such as rainfall arrival processes, storm development and decay, direction of motion relative to the river network, classification by event type (convective, frontal etc), storm scale vs catchment scale etc. These are all active research areas so definitive results cannot be expected (but may improve upon a purely stochastically based approach)
Related issues	
Multiple objective functions	Many models are calibrated against a single objective function or criterion, perhaps backed up by visual inspection of the hydrograph. However, for flood events, it is desirable for the model to represent both the full hydrograph (giving some confidence that processes are being represented) and to accurately model peaks over thresholds. This may entail evaluating the performance of different versions of the model fitted using a range of objective functions and hence parameter sets
Distribution of estimates	In sensitivity studies (particularly stochastic sampling), it is possible to derive probability distributions (or at least the variance) for the model output e.g. peak flows. These estimates can be used to place confidence limits on model output, and can perhaps be made available in real time (although note that simulation mode values may not be representative of run time values particularly when updating is used, implying that such estimates should be derived in the run time environment). Some types of model (e.g. transfer function models) are particularly well suited to this approach.
Error propagation	Except for a simple system with a single rainfall runoff or routing model, many forecasting systems include a chain of interlinked models, so sensitivity studies should assess performance and error propagation for the whole system, considering all of the different components (or interfaces) in the system e.g. rainfall forecasts, rainfall actuals, rainfall runoff models, routing models, hydrodynamic models, both with and without updating (as appropriate)

Based on this project, the following procedure is also proposed as a way of thinking about the relative magnitude of the various uncertainties in data and models and how they propagate through to uncertainties in forecasts of flows and levels. Although the final results are only indicative, they may be useful in focussing attention on those aspects of a model which generate the largest uncertainty (and it must be emphasised that this is a new approach arising out of this project which requires operational testing).

The following example is for a rainfall runoff model using rainfall actuals and forecasts to predict river levels at a site and the following table indicates the main steps in the approach. This very approximate method will give an indication of the error arising from error propagation alone and assumes a model which would be perfectly accurate if the input rainfall measurements and forecasts were known exactly. Of course all models have some intrinsic error and a common approach to the addition of random, statistically independent errors is to compute the sum of variances which, in this case, arise from the model itself, and the above errors in the input data. However, a simple addition of errors is probably sufficient here, given the other approximations in the approach, (and the presence of systematic errors as well) and will generally give larger (more conservative) estimates for the total error (and addition of variances can be used if preferred).

In the example, the model is assumed to provide forecasts for times of up to 5 hours ahead (with a catchment time to peak of 3 hours). This entails using Nimrod actuals for the first 3 hours of the forecasts, then Nimrod or radar-only forecasts for the remaining 2 hours. A linear transformation of errors is assumed with an error prediction method for correcting computed flows. The main steps in the procedure are outlined in the following table and the results for the example are presented in Table 1.16.

Table 1.16. Description of the indicative error propagation analysis

Factor	***Description***
Specify the expected accuracy in rainfall actuals and forecasts	Specify the accuracy expected in rainfall actuals and forecasts for the catchment under consideration for each lead time in the flow forecast (see the "Guidelines on Rainfall Measurements and Forecasting")
Subtract the systematic component of the errors in rainfall actuals	Many types of rainfall measurement and forecasting errors are systematic (i.e. giving consistent over or under estimation) so a view needs to be taken on whether this is the case for the catchment under consideration, since this type of error can often be accounted for to some extent in model calibration. For example, this is the usual case for raingauge data, since any single gauge (or group of gauges) is unlikely to sample the true catchment average rainfall, and many models include a gain or raingauge representativeness factor (or similar) to account for this factor. For radar actuals and forecasts, the situation is more complex since, although many errors are systematic (with a bias towards underestimation in heavy rainfall), the main products used by the Agency (Nimrod etc) attempt to correct for these factors with a result which is very dependent on the correction algorithms in the product and the catchment location relative to the nearest radar(s) (see the "Guidelines on Rainfall Measurement and Forecasting" for more details)
Transform the residual error into an error in flow peaks	The residual error in rainfall will be reduced or magnified when fed through a rainfall runoff model depending on the type of model, antecedent conditions, lead time etc and may vary during an event. Modelling studies under this project suggest that, as a first assumption, a roughly linear transformation of rainfall to flows may be reasonable for a saturated fast response catchment, and for a fixed parameter routing model, but exploratory modelling studies may be required to determine the response for other situations (and the international literature provides no definitive guidance)
Subtract the influence of the selected updating model	Updating routines can greatly improve forecasts in some situations but the nature of the correction depends on the type of updating routine used (error, state, parameter) and – for state and parameter updating – is an intrinsic (i.e. 'brand' specific) aspect of the model. Exploratory modelling studies may be required to determine the specific response of any given combination of model and updating routine. However, the following three generic behaviours provide an idea of the likely bounds on the corrections provided: • The error is distributed from zero at time now to a zero correction at the maximum lead time of the forecast. This behaviour is typical of some error prediction routines, and a linear distribution might be assumed as a starting point. • The error is distributed using the same values across the full lead time of the forecast (which can be typical of some state or parameter updating algorithms) • The error is assumed to be mainly a timing error and is removed by shifting the hydrograph along the time axis, leading to a quasi-sinusoidal variation in correction factor with lead time
Convert the remaining flow error to an error in levels	Having estimated the uncertainty/error in flows, then this can be converted to an equivalent value in levels. Typically, this will be done using an ISO-standard rating $Q=a(h+c)^b$, which for high flows (h>>c), gives the error in levels as $\Delta h/h \approx (1/b)(\Delta Q/Q)$ i.e. divide the flow error by b
Calculate the absolute error in levels	This remaining error can then be converted to an approximate error in levels by assuming a typical depth at which flooding might occur (or a trigger level reached, for example)

Table 1.17. Example of indicative error estimates for peak levels forecast by a rainfall runoff model

Factor	**Rainfall actuals (hours)**				**Rainfall forecasts**	
	0	***1***	***2***	**3**	**4**	**5**
20% error in rainfall increasing linearly to 40% two hours ahead	20	20	20	20	30	40
Assume that 10% of the error in actuals is systematic for this catchment	10	10	10	10	20	30
Assume a linear transformation of errors from rainfall to peak flows	10	10	10	10	20	30
Assume a linear decay in the updating correction (type (a))	0	2	4	6	18	30
Assume a rating exponent of 2.0	0	1	2	3	9	15
Assume a bankful level of 2 metres	0	0.02	0.04	0.06	0.18	0.30

If the model has an intrinsic error of 10%, say, assuming perfect data, then the error from this source should be added to the error in step C. Without this factor, for this example it can be seen that the errors in levels are of the order 0.1m at lead times of up to 3 hours, then increase once rainfall forecasts feed into the model (although may still be acceptable, particularly at 1 hour ahead).

However, it must be emphasised that this approach is not intended to estimate the absolute accuracy of model output but rather the relative contributions from the main factors, and sensitivity studies should be performed on the different assumptions made (including the value used for the high flow rating coefficient).

2. EXPLORATORY MODELLING STUDIES

2.1 Introduction

In addition to the review work, a number of modelling studies have been performed for specific models to explore how post event analysis techniques in the Agency might be improved and, where possible, to identify some general conclusions regarding model accuracy and error propagation which might be applied to other catchments. A particular area of interest has been the overlap in terms of accuracy between this component of the project and the rainfall measurement and forecasts component.

The types of errors investigated include:

For rainfall runoff models:

- analysis of forecast accuracy using perfect foresight of rainfall and the observed flows
- analysis of forecast accuracy using rainfall perturbed by errors corresponding to the typical errors associated with rainfall actuals and forecasts for different lead-times (primarily up to 6 hours ahead)
- where appropriate, investigations of the impact of initial conditions (catchment wetness and effective rainfall) on model output

For correlation, routing and hydrodynamic models

- analysis of model output sensitivity to input errors arising from rating equation and upstream model uncertainties, and to lateral inflows (includes correlations)
- examination of the impact of errors in key parameters which affect the model output through sensitivity analyses assuming a plausible range for the model parameters

A range of real events and synthetic data have been used for these studies using the following case study problems:

- Rainfall runoff modelling (conceptual) – River Calder at Todmorden (North East Region)
- Rainfall runoff modelling (blackbox) – River Tone at Bishops Hull (South West Region)
- Routing models (correlation, hydrological, hydrodynamic) – River Eden in Carlisle (North West Region)

Within each case study, a more general overview is also provided of each modelling approach together with some limited analyses for other catchments and using other types of model. The Todmorden case study is also used to help evaluate a range of ways of presenting model performance based on the methods described in Section 1. Conclusions from these modelling studies and the review work are presented in Section 3. The assistance of Agency staff in supplying data and calibrated models for these studies is gratefully acknowledged; however, it must be emphasised that these results are illustrative only and should not be taken as defining the performance of the particular models used since in any given situation this will depend upon factors such as:

- The nature of the flooding problem
- The quality and representativeness of the input data (particularly rainfall data)
- The number and representativeness of calibration events available
- The time and expertise available for initial model calibration

and other factors.

2.2 Model Performance – Case Study A (Todmorden, River Calder)

2.2.1 Background

The Upper Calder rises on the south eastern edge of the Pennines and the first major town is Todmorden (Figure 2.1). The Flood Warning Area lies upstream of the first major confluence which is the stream flowing down from Walsden Water. The catchment area to Todmorden is 19.6 sq.km. Forecasting problems arise from the rapid response to rainfall combined, occasionally, with snowmelt and problems from localised thunderstorms.

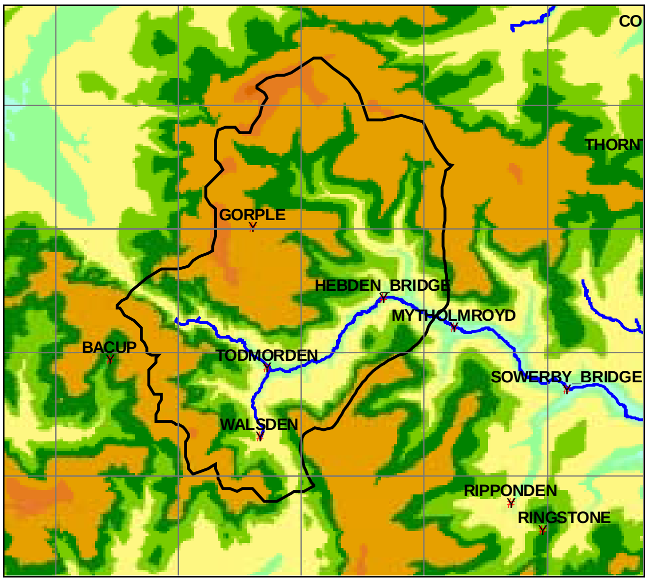


Figure 2.1. General location map for Todmorden Flood Warning Area

Flood Warning procedures are based on a combination of an at-site trigger at Todmorden gauging station, backed up by rainfall runoff modelling using a conceptual model (there are no gauging stations upstream of Todmorden which could be used for routing).

Flood Warnings for Todmorden are issued based on actual or forecast levels of 1.84m or more. The onset of flooding is estimated to be at 2.54m (1 in 25 years) based on modelling studies. The procedures also state how Todmorden levels can guide the issuing of warnings further downstream although this topic is not considered here.

The rainfall runoff model used is the Probability Distributed Model (PDM; Moore, 1985). This is a conceptual model consisting of surface, infiltration and groundwater flow components, and is one of the Real Time Models available for use within the Regional RFFS (River Flow Forecasting System). The PDM represents the conversion of rainfall to runoff assuming a range of possible probability distributions for surface soil moisture storage capacities combined with subsurface and surface runoff stores. The model has a long and successful track record in the UK and overseas, and has evolved into a 'toolkit' of modelling components which users can customise to a given situation.

The model parameters for Todmorden have recently been recalibrated as part of a Region-wide review of model performance. The standard PDM calibration shell was used for this work, permitting the model to be calibrated either in simulation mode or real time mode (i.e. with updating). There is no snowmelt module in use at present.

The main data inputs to the model are 15 minute values for rainfall at two raingauges; Gorple and Bacup. These lie on opposite sides of the valley in which the Upper Calder rises (although Bacup is just outside the catchment). Weather radar actuals and forecasts are also being considered for use with the model although the quality of the radar data has not yet been assessed. Figure 2.2 shows the catchment average rainfall and observed flows for a typical moderate sized event (October 1998).

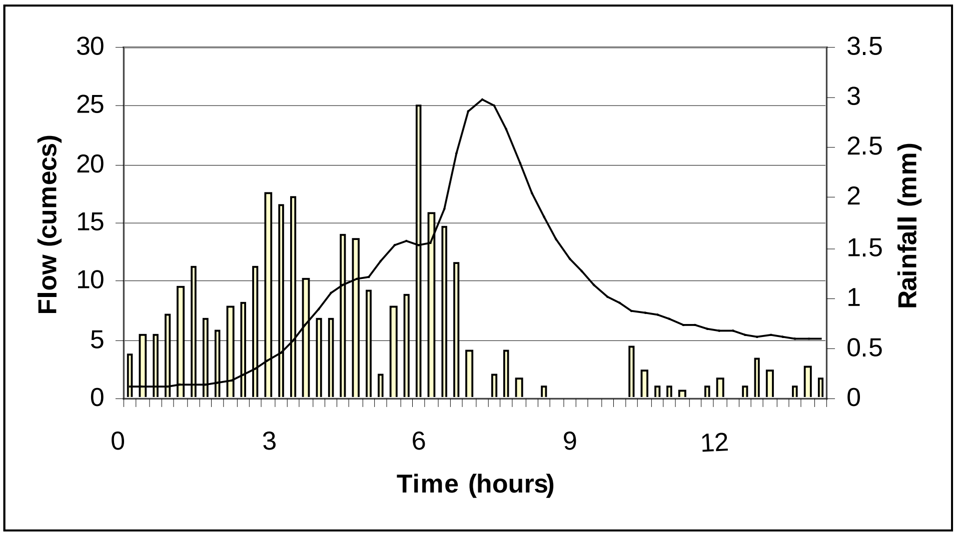


Figure 2.2. Observed flows and catchment average rainfall (October 1998 event)

2.2.2 Model Description

The model is available within North East Region both in run-time form (to operate within the RFFS) and for off-line use within a calibration shell. Parameters can be calibrated automatically using a Simplex search procedure and/or manually using an interactive graphical display. The model is typically calibrated initially using daily data for several months or more to obtain a full flow calibration, then using 15 minute data to optimise the fast response and real time updating aspects of the model.

For the Todmorden model, the standard model structure has been used of a Pareto distribution of soil moisture depths with simple recharge to the groundwater path, and a surface store comprising two linear reservoirs.

The following table shows the parameter set used for Todmorden together with the PDM parameters derived in project W242 (Environment Agency, 2000c) for three other fast response catchments. As can be seen, the parameters tend to be catchment specific although some common trends can be observed (see later).

The rating curve for Todmorden is supplied explicitly as a standard ISO three part rating with coefficients of 5.267, 0.12 and 2.174. Daily evaporation in the model is represented by a sinusoidal variation over the year, and the area weighting factors for the Bacup and Gorple raingauges are set as 0.6 and 0.4 based on a view of the representativeness of each gauge. The flood events used in the model calibration covered a peak flow range of about 10-25 cumecs (Mar 1998, Oct 1998, Jan 1999, Dec 1999, Feb 2000, Oct 2000, Feb 2001).

The model can be run without updating, or with state or error updating. When using state updating, the error between observed and forecast flows is distributed between surface and groundwater stores by adjusting the contents of the stores, and this is the form of updating used for the Todmorden model. Peak flow estimates are typically within about 20% of observed flows in simulation mode. With updating on, R^2 values are typically around 0.99 at a lead time of 15 minutes, and at least 0.93 at a lead time of 1.5 hours. Percentage errors in the peak flow are much smaller than the simulation values for short lead times (e.g. 15 minutes) and remain similar or less even at a lead time of 1.5 hours.

Table 2.1. Todmorden parameter values with three other fast response catchments for comparison

Parameter	Function	Todmorden	Trout Beck	Dove	Rhondda
Catchment area (km^2)		19.6	11.4	83	101
Rainfall factor	Controls runoff volume / raingauge representativeness	1.00	0.91	0.92	0.9
Soil moisture - Min. depth - Max. depth - Exponent	Affects time of onset of runoff and rate of wetting up, but also feeds back to evaporation and recharge rates	 1.48 29.5 3.0	 0.0 50.0 3.0	 0.0 266.0 0.2	 0.0 135.0 0.63
Evaporation exponent	Affects variation between seasons or years	2.5	1.0	2.0	2.5
Recharge model - Parameter 1 - Parameter 2 - Parameter 3	Controls rate of aquifer recharge, sensitivity of recharge to soil dryness and prevents complete store drainage	 12.9 0.0 1.06	 500 0.0 2.0	 70000 0.0 1.83	 85000 0.0 2.42
Surface storage - Time constant 1 - Time constant 2	Controls peakiness of hydrograph	 4.17 0.51	 1.6	 7.9	 3.1
Baseflow storage - Exponent - Time constant	Controls length of recession	 3 153.9	 3 5.0	 2 10.5	 3 13.0
Constant flow	Represents abstractions/discharges	0	0	0	0
Time delay	Pure time delay (if required)	0	0.13	0.25	0.17
State correction - Surface gain - Baseflow gain - Soil moisture gain	Controls real time updating using state correction	 1.38 0.37 0	 1.535 1.325 0	 1.453 1.126 0	 1.530 1.714 0

2.2.3 Model Sensitivity Studies

The above description describes the model calibration for operational use within the RFFS. The aim of the following test runs was to assess the sensitivity of the peak flows etc predicted by the model to variations in the input data and model parameters.

a) Sensitivity to input data

This set of model runs was made using the standard parameter set for the model whilst examining the impact of variations in the input data for the Bacup and Gorple raingauges.

The first set of test runs examined the sensitivity of peak flows to variations in the depth and duration of rainfall, assuming a single hypothetical catchment total value of about 25mm in 2 hours, 50mm in 4 hours and 75mm in 6 hours. These amounts were expected to generate moderate flows, flood warning conditions, and extreme flows at Todmorden respectively, and for simplicity a uniform rainfall distribution was assumed throughout. The resulting estimated peak flows were 15, 31 and 43 cumecs. Having established this baseline, these values were then changed by fixed percentages (10, 20% etc) and the impact on the magnitude of the peak flows examined. Figure 2.3 summarises the results which were obtained, together with the results of a 10% increase in actual rainfall for the 7 calibration events for comparison.

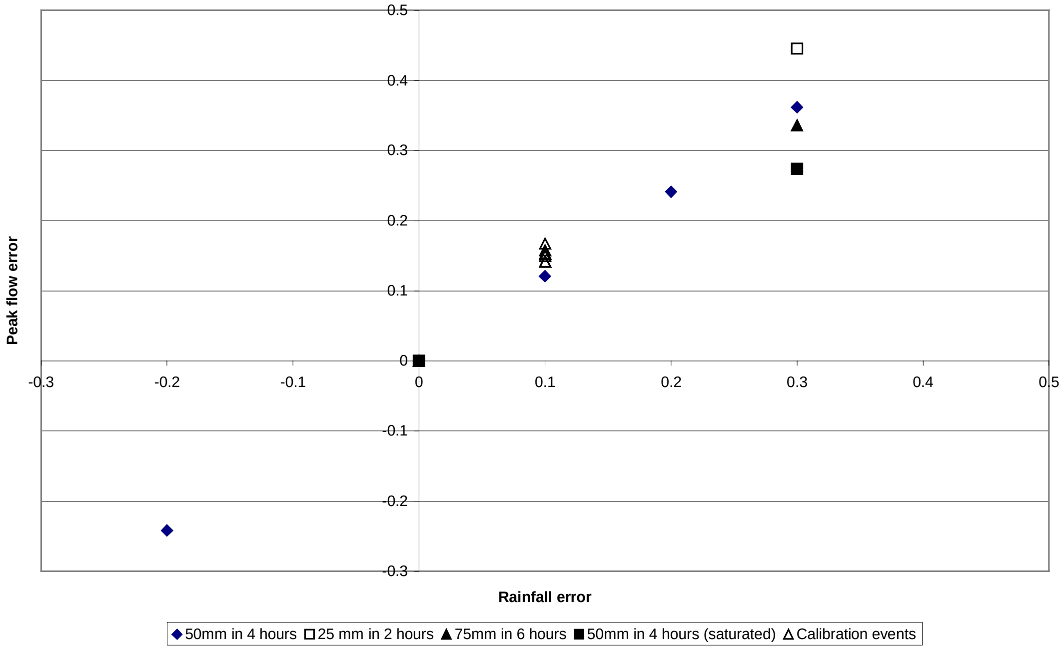


Figure 2.3. Impact of rainfall errors on peak flows in the Todmorden model (simulation mode)

These results suggest that the impact on variations in rainfall for the type of event likely to cause flooding in Todmorden is approximately linear for both underestimation and overestimation. However, the effect is lessened slightly on a saturated catchment, and amplified by a few percent for a short duration event. In terms of levels, a 10% error in flows at the levels at which flooding begins corresponds to an error in levels of about 0.1m.

b) Sensitivity to model parameters

The aim of this second set of tests was to examine the sensitivity of the model results to typical variations in the model parameters.

A common feature of many conceptual models is that, for a given modelling situation (e.g. recession behaviour, flood flows) there is usually a subset of parameters which have the main influence on model output, and an inspection of Table 2.1 would suggest that, under flood conditions, the key parameters to consider for this model are those relating to the soil moisture storage and surface and base flow time constants. The area averaging procedure used for rainfall data (Bacup/Gorple) is also another important factor.

Also, the PDM is one of a number of conceptual models being evaluated within the general area of ‘continuous simulation’, which is an active research area to develop models capable of estimating flood flows for ungauged catchments by relating model parameters to catchment characteristics. For the PDM, for example, recent studies (e.g. Lamb *et al*., 2000) have suggested that a slightly more extensive set of parameters is key to generalising the model for this type of regionalisation study:

- Rainfall factor
- Soil storage max. depth
- Surface storage time constant
- Baseflow storage time constant

For these sensitivity studies, a subset of these parameters was chosen as indicated in the following table, together with the impacts on peak flows for the 7 calibration events.

Table 2.2. Sensitivity of peak flows (in %) to variations in model parameters for the 7 calibration events (simulation mode)

Parameter	Run 1	Run2	Run 3	Run 4	Run 5	Run 6
Mar 1998	-4	1	-72	2	15	-2
Oct 1998	-3	1	-70	2	13	-2
Jan 1999	-4	1	-75	0	15	-2
Dec 1999	-5	1	-80	1	16	-1
Feb 2000	-4	1	-73	2	14	1
Oct 2000	-3	1	-71	1	14	-3
Feb 2001	-4	1	-72	1	15	-2
Gorple/Bacup						0.5/0.5
Rainfall factor					+10%	
Soil moisture						
- Min. depth						
- Max. depth	+10%					
- Exponent		+10%	>-90%			
Evaporation exponent				Zero		

These results confirm the anticipated result which is that the impact of varying parameters over a small range (say 10%) is generally much less than that caused by similar variations in the input rainfall data or rainfall factor, and even major changes in some parameters have little effect where they have little relevance to the surface runoff process (e.g. reducing the evaporation exponent to zero). However, when, as in Run 3, a key parameter is varied by a large amount, the impact on flows can also be large, particularly when, as in this case, no compensating adjustment is made to related parameters to account for parameter interdependence.

2.2.4 Application to other Catchments

The results for Todmorden of course apply to only one catchment so the aim of this section is to attempt to generalise these results by focussing on those aspects of the model to which the predicted flows are most sensitive, and bringing in results from other fast response catchments for comparison.

The model runs for Todmorden indicate that the catchment has the following features which are typical of many fast response catchments:

- High runoff coefficient (on an event basis)
- Small time to peak
- Model runs sensitive mainly to the fast response pathway aspects of the model

This response might therefore by modelled by a simpler model, which concentrates on the surface runoff components of the problem. In the PDM model, the representation used for Todmorden is a cascade of two linear reservoirs in series. However, other representations are available within the PDM and include quadratic, exponential and general non linear formulations.

More generally, one particularly simple conceptual model is the Isolated Event Model (or IEM), which assumes a quadratic surface store and a runoff coefficient which is an inverse exponential function of the soil moisture deficit at the start of the event. Due to its wide application in UK conditions, this particular form provides the potential to explore the fast response aspects of conceptual models in more detail (whilst not considering the full flow range performance provided by more sophisticated conceptual models such as the PDM).

a) Isolated Event Model

This model was first proposed in the 1970s for flood design studies in the UK's Flood Studies Report (predecessor to the Flood Estimation Handbook) and the evaluation studies remain one of the most comprehensive to date for a conceptual model under UK conditions, although the results were never widely used except for research. However, the model has recently been evaluated in a modified form (real time updating, triangular time delay function etc) as part of project W242 (Environment Agency, 2000c), where it was found to perform at least as well as some more complex models on fast response catchments. Also, for small catchments, a similar model (the ISO model) has recently been suggested as ‘effectively the model to beat for real time forecasting’, and the whole area of event based rainfall runoff models may soon be revisited as part of the ‘revitalisation of the FSR/FEH rainfall runoff method’ project which is just starting (see Part C).

In the Flood Studies Report, the IEM model was evaluated in simulation mode against data for 500 events on 21 catchments with catchment areas up to about 500 sq. km. Calibrations were performed using a Rosenbrock optimisation algorithm based on a root mean square optimisation function. Figure 2.4 summarises the performance of the model as a function of lead time in terms of the R^2 statistic and the mean error in peak flow and event total volume.

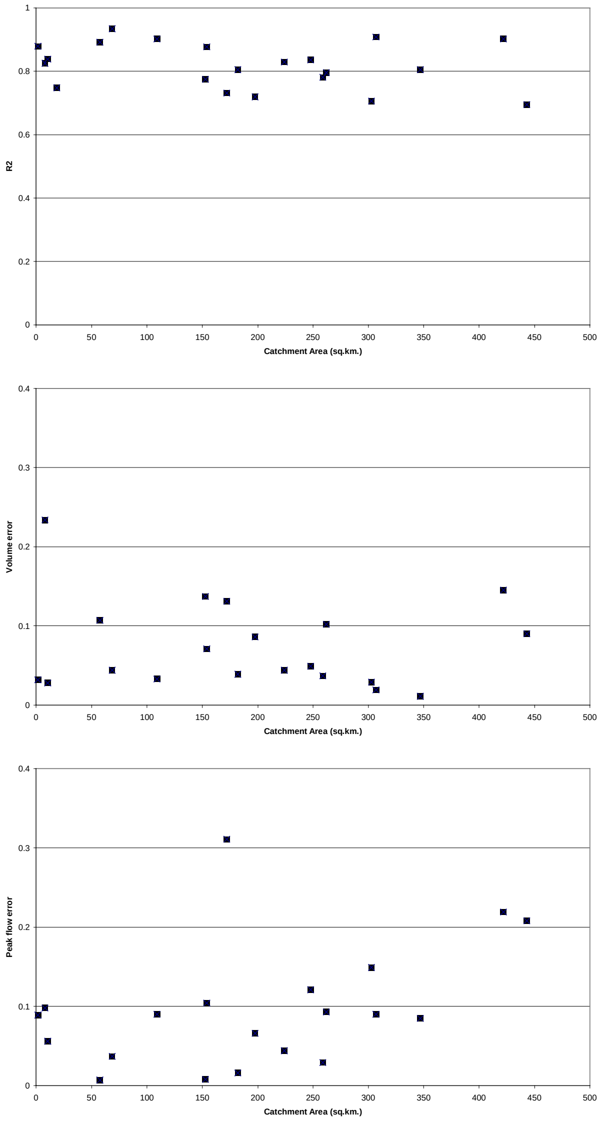


Figure 2.4. Variation in model performance with catchment area for the IEM example catchments

Absolute errors in peak flows do not seem to show any trend with time to peak or catchment size and typically average less than 10-20% between events. By contrast, the two volume based measures (volume over threshold, R^2) are slightly better for smaller catchments, although there is little discernible trend visible.

Given that the R^2 statistic is widely used for reporting model performance, the following figure shows that this measure alone is not necessarily the best indicator of the model performance with respect to other aspects of the hydrograph (e.g. peak values or event volumes), with little discernible relationship between these different measures (at least for the IEM model in simulation mode).

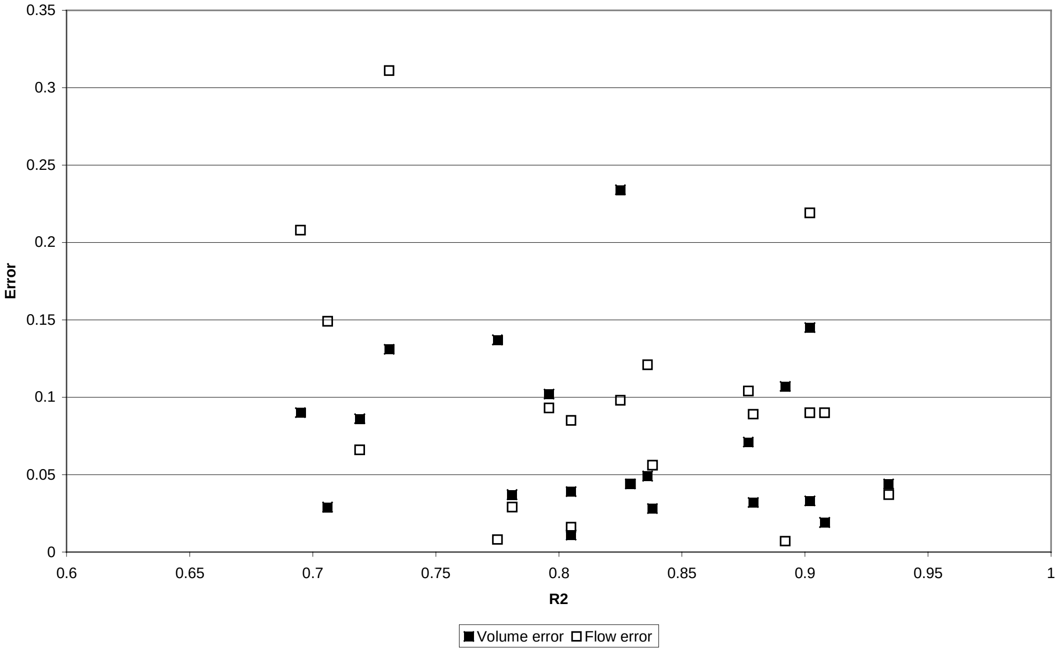


Figure 2.5. Relationship between the R^2 coefficient and volume and peak magnitude errors for the IEM example catchments

For an isolated (single) peak, with a uniform error over the full flow range, the relationship between the fractional error in peak flows, and R^2, is given approximately by $\Delta Q/Q \approx \sqrt{}(1-R^2) / N$, where N=2. Simulation studies (see Figure 2.6) indicate that, for a typical single peaked hydrograph, this equation provides a reasonable representation of this relationship when there are no timing errors. However, the figure also shows how even a small timing error (here 3 or 6 % of the timebase of the hydrograph) can significantly reduce the R^2 value for a given peak flow error. Results will generally be model and site specific, but for the IEM model values given in Figure 2.5 the value of N is approximately 6 (rather than 2) i.e. an R^2 of 0.8 corresponds to a maximum peak error of approximately 10%. This result might possibly be applied to other types of model and has been tentatively suggested in Section 1.7 as a way of relating these two statistics describing model performance (although site specific results are to be preferred).

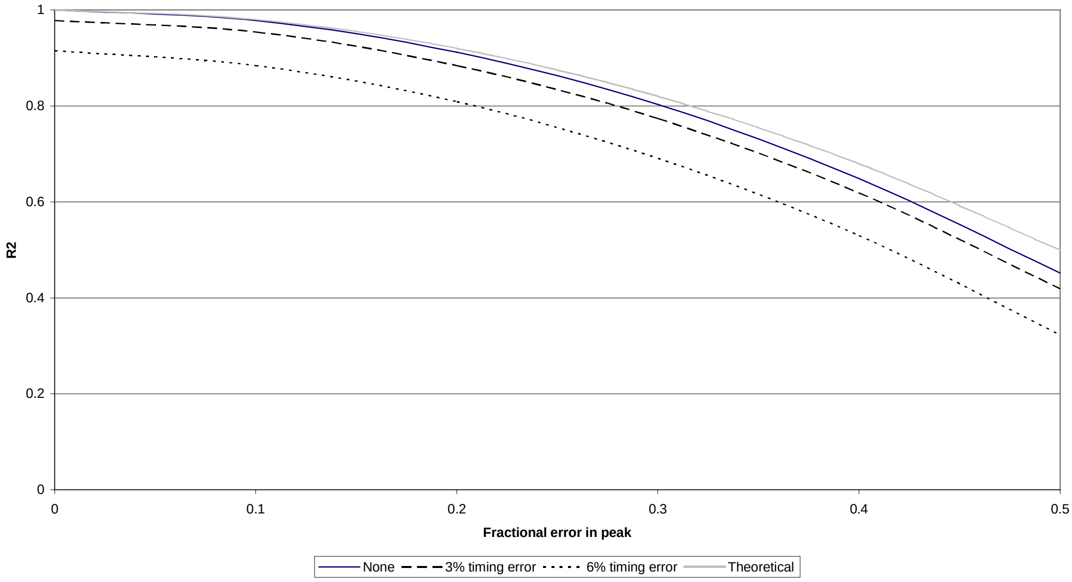


Figure 2.6. Relationship between peak flow error and R2 for various assumed timing errors for an idealised single peak

More generally, one of the aims of these modelling studies was to explore new ways of presenting information on model performance, and obviously it is not only the mean error which is of interest but also the likely spread of errors between models, sites and/or events. The FSR IEM results also include estimates for the standard deviations of timing and magnitude errors for the 21 catchments and Figure 2.7 shows one possible way of presenting the results in the form of ellipses or ‘bullseye’ plots centred on the mean error, but with axis lengths proportional to the standard deviations of errors. If errors were to be normally distributed, then approximately two thirds of values would then lie within this range (although a normal distribution will not necessarily be obtained).

In this example, the spread of errors is typically within 20-30% of the actual peak, with timing errors typically within 2 hours of the peak. However, for a few catchments (typically larger catchments), errors are larger than this, and these ‘ellipses’ are shown in a lighter shading. Plots of this type give an idea of both the magnitude and spread of errors, and could of course be refined further if wished (for example, presenting the timing error as a non dimensional ratio to the time to peak to indicate the relative scale of errors, and using different shades to indicate where ellipses overlie each other, and hence errors are concentrated).

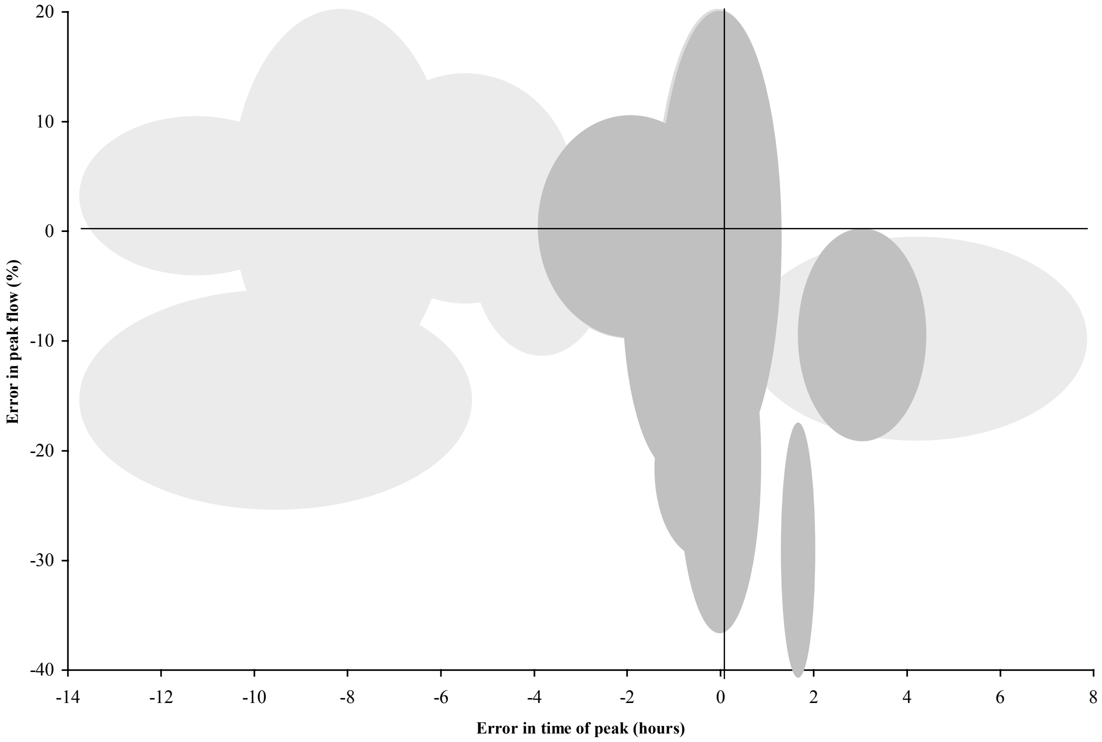


Figure 2.7. A novel way of presenting both the magnitude and spread in peak magnitude and timing errors (example for the IEM model)

The main conclusions from the FSR study were that the model was more successful for steep upland catchments than for slow lowland rivers, and should not be used for events involving snowfall or frozen ground. Suggested improvements included:

- Addition of a time area element into the model for larger catchments
- Variation of runoff ratio during a storm (evaluated during Project W242)
- Variable model parameters between events
- An improved soil moisture accounting model

It should be noted that all of the results presented so far are for the model in simulation mode. When state updating is used, results for an additional 8 catchments (see Environment Agency, 2000c) suggest that R^2 values of 0.9 or more are achievable on small fast response catchments even at the maximum lead time available.

It is also interesting to apply the IEM model to the Todmorden catchment and, to do this, the PDM calibration results were used as a guide, with a similar runoff coefficient, initial soil moisture deficit, pure lag time etc which left only one parameter to tune, which was the time constant for the quadratic store. Figure 2.8 shows an example of results obtained for simulation mode for the October 1998 event at Todmorden together with the 1 hour ahead forecast using updating, and show that the model provides a reasonable estimate for the peak and recession, although with a timing error of about 15 minutes, and some overprediction of the minor event on the rising limb of the hydrograph.

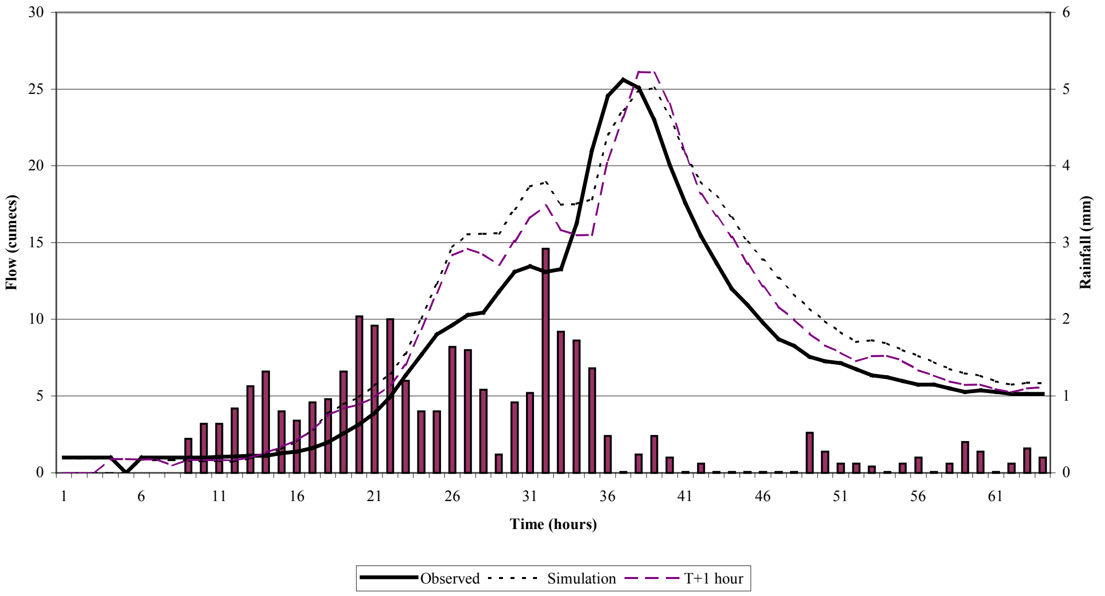


Figure 2.8. Comparison of observed and forecast flows for Todmorden using the IEM model

In this figure, the updated values are obtained using a simple 'blending' model which aims to emulate the characteristics of some error prediction models i.e. that observed and forecast flows match at time now, and the forecasting error is assumed to decay linearly to zero at the maximum lead time available in the forecast. For this simple model, it can be seen that the simulation mode values provide a reasonable representation of the flood peak magnitude and shape, and that this crude updating scheme provides some improvement (although a statistically based error prediction routine, or state updating approach, should perform better than this). Figure 2.9 summarises the results for peak magnitude errors for the model for all 7 calibration events and shows that this particular version of the model predicts peak flows to within about 20%, and better for high flows.

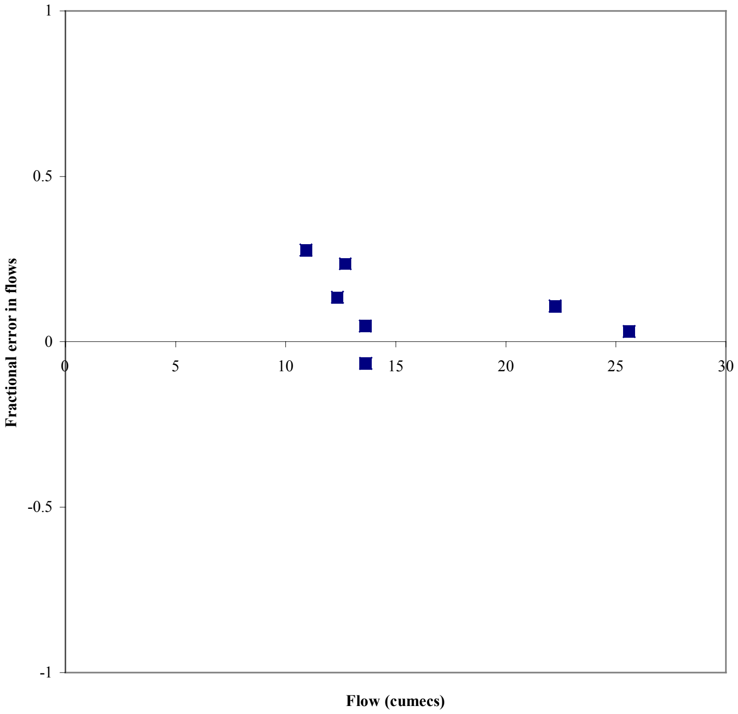


Figure 2.9. Peak magnitude errors for the 7 Todmorden calibration events using the IEM model (30 minute ahead forecasts)

b) *Propagation of rainfall errors*

Although the PDM studies (see earlier) investigated model sensitivity to rainfall errors, this was in simulation mode whereas updating mode would typically be used in real time operation. The main interest now is to examine how this behaviour is modified for the case of a rainfall error which increases with increasing lead time (corresponding to typical behaviour in rainfall forecasts) and with updating used.

The "Guidelines on Rainfall Measurements and Forecasts" present the following assessment for the accuracy of the Met Office's Nimrod product for delivering radar rainfall actuals and rainfall forecasts.

Table 2.3. Indicative summary of Nimrod accuracy estimates for hourly and other accumulations over storm areas of 100-200 sq. km or more in heavy rainfall (draft for discussion/review)

Range/lead time	**0-50km**			**50-100km**			**100-250km**		
	POD	RMSF	% error	POD	RMSF	% error	POD	RMSF	% error
Actuals	94-98	1.7-2.3	10-20	94-98	2.0-2.3	20	50-94	2.3-2.6	20-40
1		2.4	Similar		2.4	Similar			
2		3.7			3.7				
3		4.2			4.2				
4		4.3			4.3				
5		4.4			4.4				
6		4.4			4.4				
0-3	60			60					
3-6	32			32					
0-6			10-30						
Storm total			20						

The Todmorden catchment lies within 50 km of the Hameldon Hill radar and the radar quality class is the second highest available (on a scale of seven). Thus, for the lead times of interest for Todmorden (up to about 2 hours ahead), it might tentatively be suggested that radar actuals might have errors of 10-20% and forecasts for frontal events might be of slightly lower accuracy than actuals at lead time of 1 hour, and perhaps with errors roughly twice as large at 2 hours. Rather than attempt to specify the precise errors (which, for a given location, depends on many factors, and requires a pilot study), it is more instructive to examine the sensitivity of model forecasts to a range of hypothetical errors (or, more correctly, uncertainties, in rainfall forecasts).

For these scenarios, raingauge data were taken as 'truth' (i.e. perfect foresight of rainfall) but perturbed by errors growing linearly to -20%, -10%, +10% and +20% at a lead time of 1.25 hours. The following figure shows an example of the results obtained for the +/- 20% scenarios with and without updating.

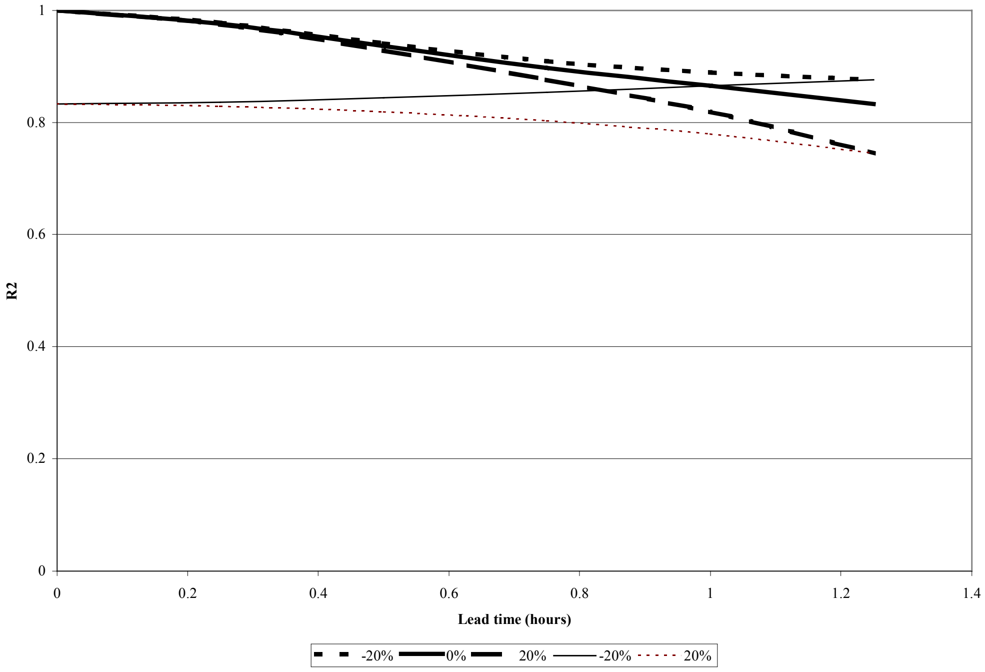


Figure 2.10. Example of the impact of rainfall error propagation on Todmorden IEM forecasts in simulation and updating modes (October 1998)

The results for this event are not clear cut with rainfall errors appearing to actually improve the forecast slightly in some situations at longer lead times (with updated and simulation mode values converging due to the nature of the updating routines used). However, an examination of the forecast hydrograph shows that this behaviour is due to the model predicting the mid range flows better on the rising limb, at the expense of a worse prediction for peak flows. Nevertheless, for updating mode, the classical behaviour in R^2 with lead time is retained at the expense of a variability of about 0.05 at lead times of 1.25 hours, but negligible impact below about 1 hour. In terms of peak flow values (Figure 2.11), the changes are more pronounced reaching about 5% at a lead time of 1 hour, but still remain below half the errors in the input rainfall data.

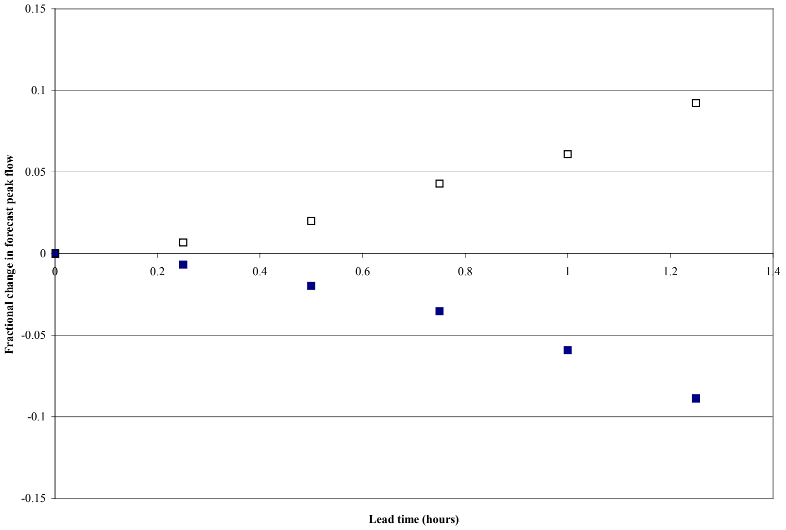


Figure 2.11. Example of the impact of rainfall error propagation on Todmorden IEM forecasts of peak flows in updating mode (October 1998) (+/- 20% rainfall errors at 1.25 hours)

2.2.5 Conclusions

These modelling studies for Todmorden Flood Warning Area have suggested the following general results which might be applied to other fast response catchments in which conceptual rainfall runoff models are used to forecast flows:

- Although mechanisms such as infiltration and baseflow can be important at moderate flows, under flood conditions the fast response pathway in the model often provides a good representation of the runoff response. Model calibration should therefore focus on achieving the optimum values for this aspect of the model (and accounting for parameter interdependence)

- Under flood conditions, the bulk of the runoff comes from total rainfall, rather than effective rainfall, although with many conceptual models this is handled automatically so is not a concern to the user

- Even a simple updating scheme such as that used here can dramatically improve the performance of the model at short lead times, although the magnitude of the improvement varies between events and the performance statistic being examined (for example, peak flow estimates may improve at the expense of the R^2 statistic). Error reductions of more than 50% were achieved even with the simple scheme used here.

- When the fast response pathway dominates response, error propagation from rainfall data appears to be roughly linear in simulation mode. In updating mode, the error is again greatly reduced (but the amount of the reduction depends on the type of the updating scheme used and will often be model 'brand' specific).

- The results confirm the results of previous studies (e.g. Environment Agency, 2000c) that a simple model such as the IEM can perform surprisingly well on fast response catchments under flood flow conditions (particularly with updating). Successful case studies for more than 20 catchments in England and Wales have now been documented in the literature. This suggests that more complex models should adopt a similar structure for the fast response pathway (as is the case for the PDM, for example). However, it is important to note that, for low and moderate flows and initially dry conditions, the performance of a simpler model such as the IEM will deteriorate due to the minimal representation of antecedent conditions in the model.

- For presenting model results, the fractional error in peak flows and the R^2 statistic are useful for fast response catchments. In the absence of timing errors, these statistics are related approximately by the relationship $\Delta Q/Q \approx \surd\,(1-R^2)\,/\,N$, where N=2, but for the models examined here, a value of N=6 seems more representative when timing errors are present (in the absence of updating)

- In considering model performance, it is also important to examine the spread of the estimates, as well as the mean value. A novel presentation using ellipses centred on the mean timing/magnitude error, with axis lengths proportional to the standard deviation of the estimates, provides a convenient way of summarising results for many sites and events.

2.3 Model Performance – Case Study B (River Tone)

2.3.1 Background

The headwaters of the river Tone rise at approximately 400m above sea level in the Brendon Hills (Figure 2.12). Flows in the upper 5% of the catchment are controlled at Clatworthy Reservoir, below which the river runs through a steep narrow valley to Greenham gauging station, opening out considerably to form a flat and wide floodplain with gently rising valley sides. From here the river flows through agricultural land to Taunton and then on through the highly managed, flat, alluvial plains of the Somerset Levels. Flood warnings are issued both for the urban centre of Taunton and for the Somerset Levels, where prolonged high flows can cause serious flooding.

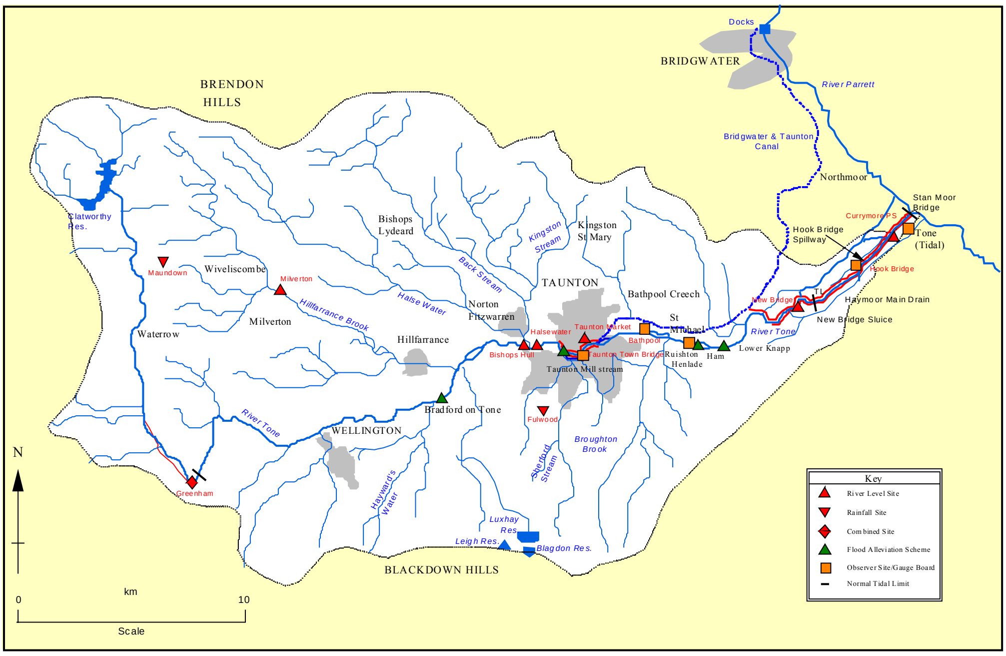


Figure 2.12. General location map for the Tone catchment

Travel times through the catchment are rapid and the time to peak, based on observed data, has varied between 6.5 and 18 hours for Greenham and 13 and 23 hours for the Bishops Hull gauging station (catchment area 202 sq.km., Crump Weir). Figure 2.13 shows an example of rainfall and flows for one of the largest high flow events in recent years (Jan 1999).

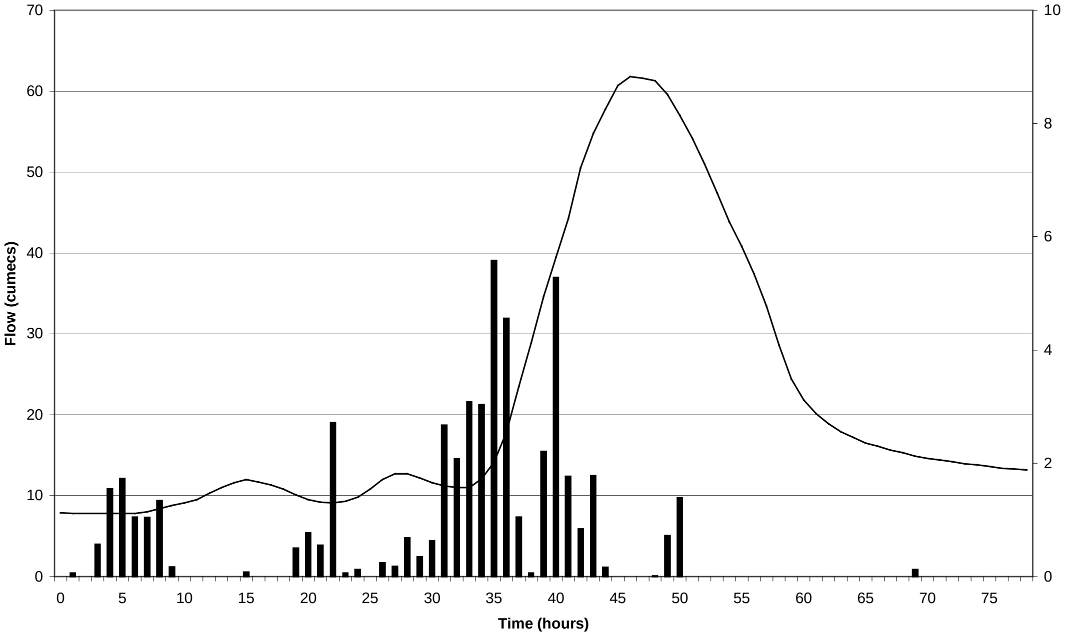


Figure 2.13. Catchment total rainfall and flows at Bishops Hull (January 1999)

Flood warnings for Taunton are presently issued based on at site triggers with a flow of 60.5 cumecs triggering a severe flood warning for the lower Tone and a flow above 67.1 cumecs triggering a Major Incident Plan for Taunton. A transfer function based approach is also being considered, and the following description is based on reports, datasets and spreadsheets provided by Regional staff for use on this project.

The type of model being assessed is a Physically Realisable Transfer Function (PRTF) for flows to Bishops Hull and then levels using the station rating curve. The model uses catchment average rainfall estimated by Thiessen polygons from data for Maundown and Fulwood raingauges. The model has been calibrated within a bespoke software environment and is intended for operation within the Regional WRIP system environment. Figure 2.14 shows an example of application of the model to an event on the 19th September 1999.

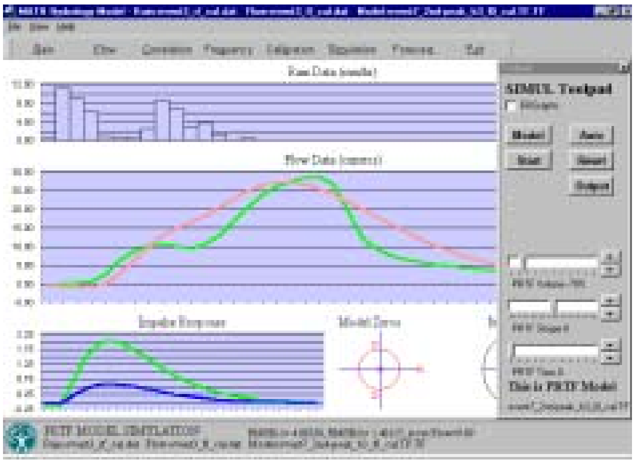


Figure 2.14. Example of the model output in simulation mode for the event of 19th September 1999

The model can be updated manually either at the onset of an event or in real time by adjusting the volume, shape and lag parameters of the model, and guidelines are being developed to relate these parameters to antecedent catchment conditions at the start of an event. Investigations are also being undertaken into the impact of the use of effective rainfall in flow forecasting and on methods of defining effective rainfall (see below).

These manual updating methods are applied to the results from the model in simulation mode, and an alternate automated updating technique is to reinitialise the model at each time step using the actual or smoothed observed flows up to 'time now'.

2.3.2 Model Calibration

The PRTF model was developed by Han (1991) as a form of transfer function in which the output is constrained to be stable and non oscillatory. The model uses estimates for catchment rainfall to derive flows where the rainfall can be either the measured (total) value, or a value called the effective rainfall corrected to allow for losses due to infiltration etc.

For Bishops Hull, the basic total rainfall model was recalibrated by Agency staff in mid-2000 to provide a choice of four parameter sets, all with the same structure (flow parameters, rainfall parameters, lag time), but assuming different parameterisations of rainfall inputs (total, effective rainfall etc).

The updating parameters to use in an event are obtained from the following lookup table which was derived from data for 8 high flow events.

Table 2.4. Updating parameters for the model

Season	CWI	Volume	Volume	Shape	Time
‘Summer’	<50	15	-70	0	0
‘Summer’	50-100	25	-50	0	0
‘Spring/Autumn’	100-125	35	-30	0	0-1
‘Winter’	125-140	43	-15	0	0-1
‘Winter (saturated)’	>140	100	0	0	0

Hence, for a saturated catchment in winter, when infiltration losses are minimal, and flood risk highest, the simulated flow is taken as correct whilst, for all other conditions, various degrees of adjustment are made, rising to some 70% on a dry catchment in summer. When updating is used, these volume, shape and timing values are used within the model to adjust the parameter values to achieve the required ‘tuning’ of the hydrograph. For high flows, the model typically predicts the peak flow to within about 5%, with timing errors of 45 minutes at worst.

Work is now continuing on evaluating the performance of the model using effective rainfall, rather than total rainfall, as an input. The algorithm being evaluated is based on that used in the IHACRES software, which is a parallel pathway transfer function model developed by CEH and CRES, Australia.

The basis of the model is to use air temperature as a surrogate for the influence of evapotranspiration on catchment wetness. A simple soil moisture accounting model is used to relate current soil moisture (via a Catchment Wetness Index) to a weighted sum of the total rainfall and the soil moisture at the previous time step (Jakeman *et al.*, 1990).

The weighting for the catchment wetness index depends on an exponentially decaying function of air temperature, with a time constant (the catchment drying constant) approximately equal to the rate at which the wetness index declines in the absence of rainfall. The weighting for rainfall is an adjustment factor chosen to preserve volume between effective rainfall and runoff during the event.

For the Bishops Hull model, the model was recalibrated using data for the period March-May 2000. In simulation mode, the model was found to offer some improvements in predicted peaks for some events but overall the forecasts were not greatly improved for this calibration period. Examining more events over a longer period showed some improvement although with doubts about the contribution from baseflows to flows when the catchment is not saturated.

Figure 2.15 shows an example of the impact of the effective rainfall component of the model for the calibration events, where the runoff has been expressed as an equivalent depth using the catchment area. For the largest events, the percentage runoff over the whole event is typically 0.6-0.7. In some cases, the effective rainfall component acts to reduce this to a value near to 1.0 (or, in terms of rainfall, the effective rainfall is estimated to be approximately two thirds of the total rainfall).

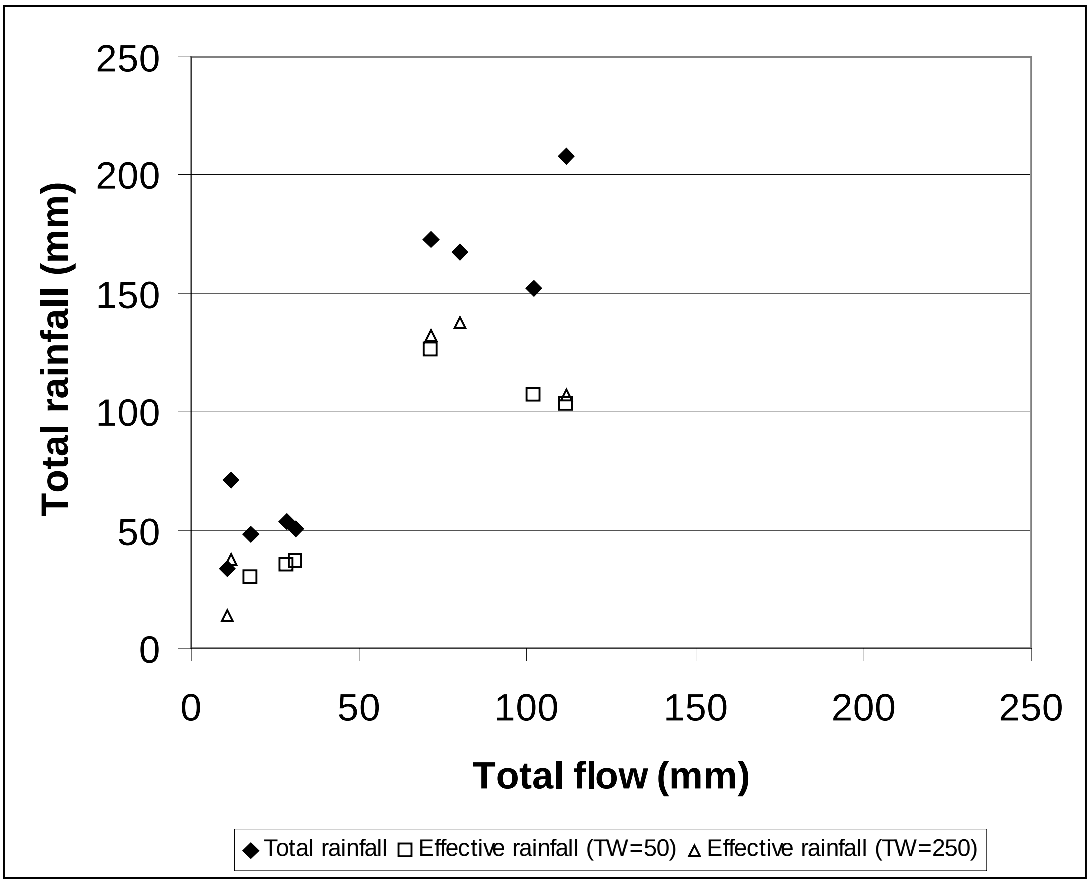


Figure 2.15. Impact of the effective rainfall adjustment for nine calibration events

2.3.3 Model Sensitivity Studies

Of the calibration events available, the January 1999 event is the largest in terms of peak flows and has been used for these sensitivity studies. The main impacts to investigate are the effects of the effective rainfall formulation and of errors in input data (variations in model parameters have less meaning for transfer function models since all parameters are interdependent i.e. changing one requires changes in all others).

Figure 2.16 shows the impact of the effective rainfall formulation for this event, using one of the four effective rainfall parameterisations.

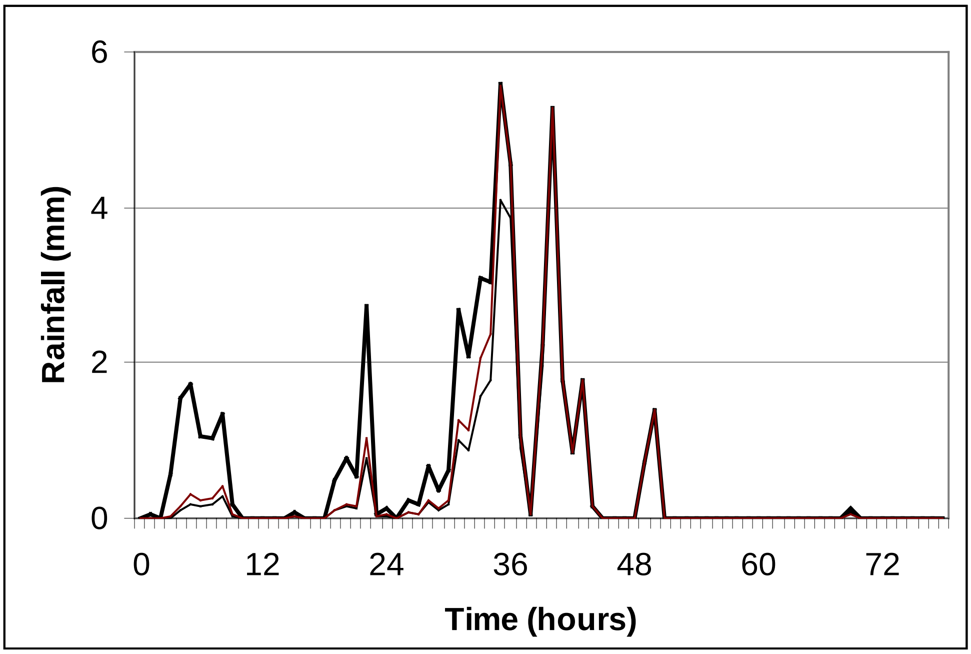


Figure 2.16. Comparison of effective and total rainfall for the Jan 1999 event

For the main peak, the main impact is on rainfall losses in the run up to the peak itself, with an expected impact on the magnitude of the peak. This can be seen from the following table, in which the peak flow is reduced by some 21% for this particular scenario.

Table 2.5. Indication of impact of rainfall errors on flows for one effective rainfall formulation

Rainfall formulation	Multiplying Factor	Percent error in peak	R^2
Total	1.0	9	0.90
	1.1	17	0.82
	1.2	24	
	1.4	40	
	0.8	-8	
	0.9	0	
Effective	1.0	-12	0.89

Table 2.5 also shows the impact of a range of errors in total rainfall and, as might be expected from the structure of the model, the sensitivity to effective rainfall is roughly linear when the difference between effective and total rainfall is small. The effect of this particular effective rainfall formulation, for this event, is roughly equivalent to a 30% change in total rainfall.

One way of examining this response in more detail is to run the model to steady state, and then to apply a hypothetical error in rainfall, as indicated by the following figure:

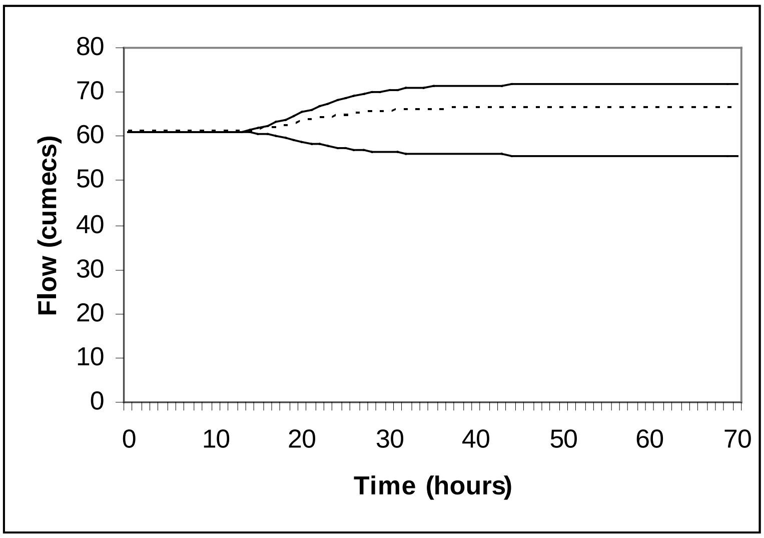


Figure 2.17. Model sensitivity to errors of +10%, +20% and -10% in total rainfall under steady state conditions

This shows again that response is roughly linear and propagates over a timescale of about 10 hours; however, as in Table 2.5, the results apply to simulation mode whereas in practice PRTF models are often operated in real time with some type of updating.

The main options available for updating are:

- Adjusting parameter values (indirectly) using volume, shape and timing corrections (see Table 2.4)
- Reinitialising the model at every timestep based on observed flows
- Using an independent error correction routine

To illustrate the likely magnitude of updating, two approximate automatic updating methods have been used for this case study; reinitialising and the crude error blending technique discussed in the Todmorden case study. Figure 2.18 illustrates that, for both methods, similar results are obtained, and that the impact of rainfall data/errors is dramatically reduced at short lead times, as illustrated by the run using zero rainfall as input (although this effect decays at longer lead times).

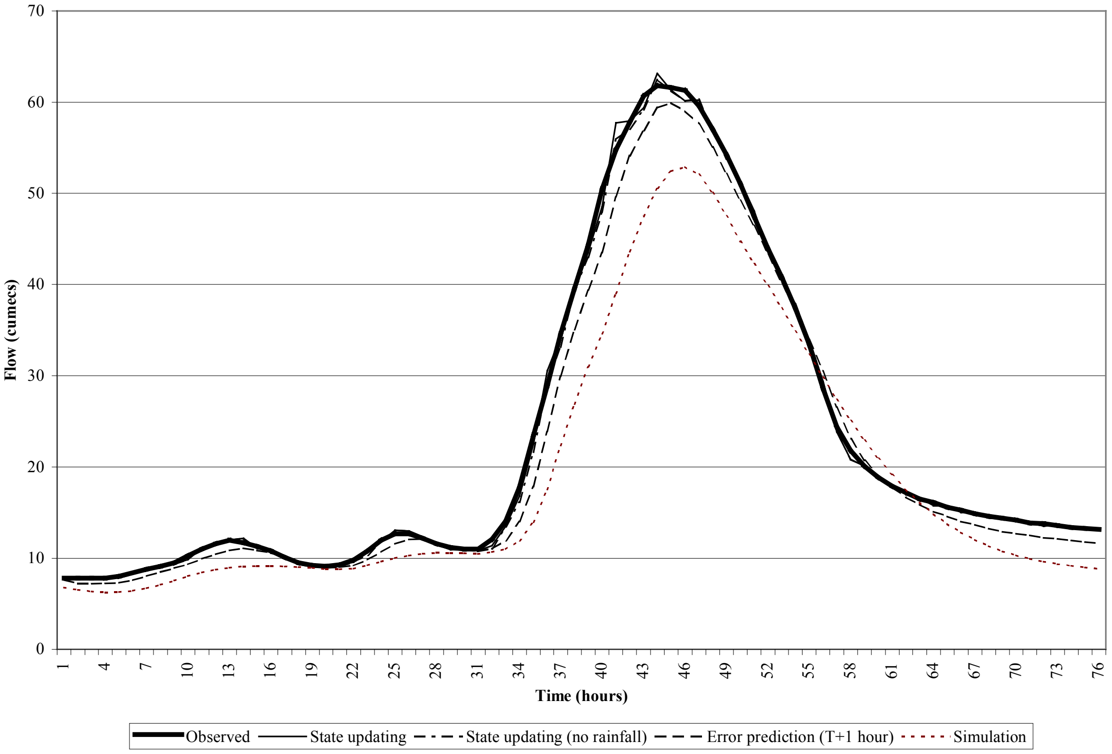


Figure 2.18 Indicative results for two updating procedures

This result arises from the relative magnitudes of the parameters of the model for flow and rainfall, which sum to 0.99 and 0.36 respectively. For simulation mode, errors in total rainfall feed through in full to errors in flow, whereas in updating mode (at least at this short lead time), the flow aspects of the model dominate; for example, for a typical peak flow of 60 cumecs, and rainfall of 5 mm/hour, in quasi-steady state conditions the relative contribution of the rainfall term is much smaller than that for flows.

Thus, for this particular version of the model (there are others) the historical data point towards a model which relies primarily on flow persistence for forecasting when in updating mode. The ratio $\sum b_i/\sum a$ of the flow to rainfall parameters (a_i and b_i, say) provides an indication of the sensitivity of the model to rainfall errors (and is related to the steady state gain). The following table shows the wide range of values which can occur for some of the transfer function models which have been evaluated for Agency use:

Table 2.6. Steady state gains for some Agency Tranfer Function models

Region	**Location**	$\sum a_i$	$\sum b_i$	$\sum b_i / \sum a_i$
Anglian	Willow Brook at Fotheringhay	0.92	0.09	0.09
	River Croal at Blackford Bridge	0.93	1.13	1.21
North West	River Greta at Low Briery	0.99	0.29	0.29
South West	River Tone at Bishops Hull	0.99	0.36	0.36

For example, the second of the Anglian models is likely to show a higher sensitivity to rainfall errors than the examples given for South West and North West Regions (although this of course is not a general result and will depend on the individual model, catchment etc).

2.3.5 Conclusions

These modelling studies for the river Tone have suggested the following general results which might be applied to other fast response catchments in which transfer function rainfall runoff models are used to forecast flows:

- Under flood flow conditions, a model based on total rainfall can sometimes provide a reasonable representation of catchment response (although this will deteriorate for low to moderate flows)

- When total rainfall is used, error propagation from rainfall to runoff is approximately linear in simulation mode, with errors greatly reduced in updating mode.

- An examination of the model's response characteristics under steady state conditions can be informative and can highlight the importance of rainfall in the model when using real time updating

- Updating routines for transfer function models have very different characteristics according to both the type of model and the type of updating routine. For example, for a linear model, state updating can greatly reduce the impacts of errors in rainfall data, whereas the effects are less pronounced for error correction methods.

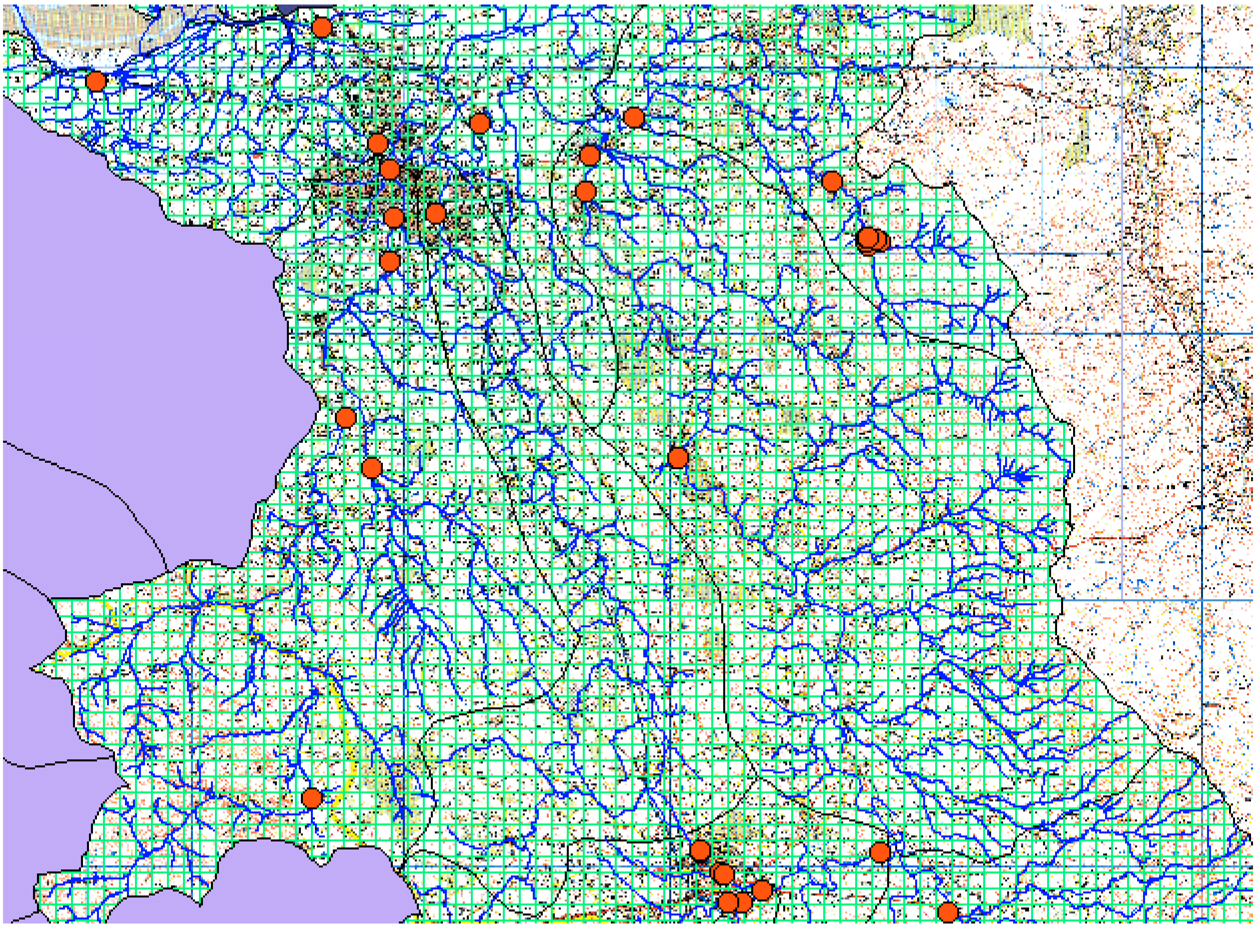
2.4 Model Performance – Case Study C (River Eden, Carlisle)

2.4.1 Background

The river Eden and its tributaries rise in the eastern Lake District and western Pennines and cover an area of 2404 km^2 with a maximum elevation of 930m. The catchment is predominantly rural and undeveloped with the exception of three main towns, Carlisle, Penrith and Appleby, with the main flood risk being in Carlisle (Figure 2.19).

Figure 2.19. Location map for the Eden catchment

The main tributaries include the Rivers Caldew, Petteril, Eamont, and Irthing. The Eamont flows down from Haweswater (via the Lowther tributary) and Ullswater to join the Eden east of Penrith more than 30km upstream of Carlisle and the Irthing joins approximately 9 km upstream of Carlisle. Two major tributaries, the Caldew and Petteril, join within the Carlisle City boundary. Figure 2.20 shows indicative values for the mean annual flood on these tributaries. There is a limited floodplain on both these rivers and the Caldew passes mainly through the urban areas of Carlisle.



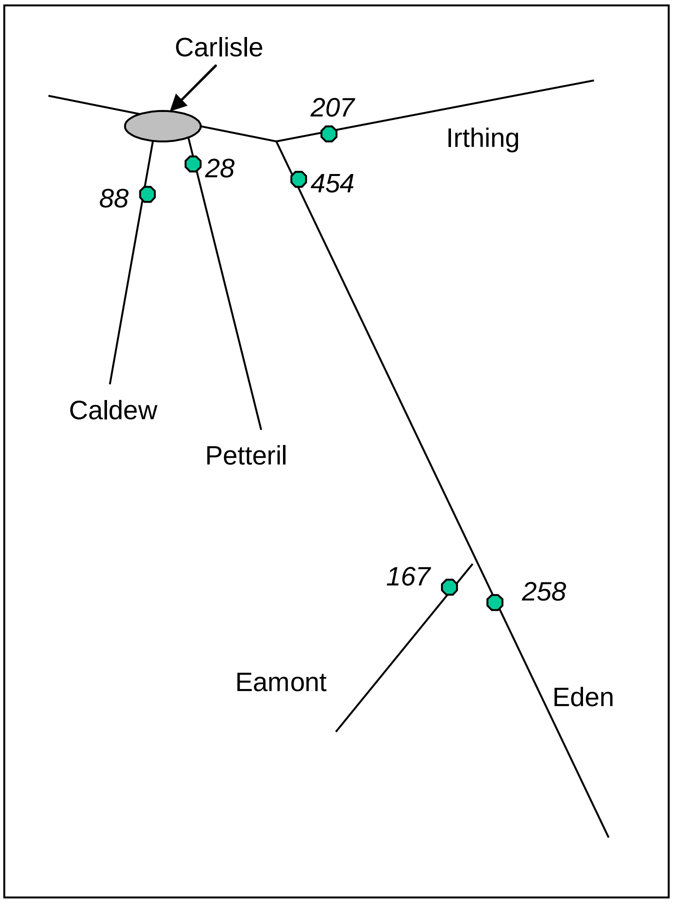


Figure 2.20. Indicative mean annual floods for the main tributaries of the Eden

The rainfall over the catchment varies considerably with an average annual rainfall of approximately 3800 mm to the south of Haweswater, and 760 mm to the south of Carlisle. The highest points in the catchment are Skiddaw at 931m at the head of the River Caldew and Helvellyn at 950m.

The main gauging stations in the reach down to Carlisle are at Temple Sowerby on the Eden upstream of the Eamont confluence, and Udford on the Eamont. From Temple Sowerby down to Carlisle there is no major floodplain and the main flooding occurs just below the confluence with the Eamont. The total floodplain area is about 7 sq.km. in this 37km reach (i.e. only about 0.2 km^2/km), and the mean slope is about 0.0017 with a maximum of 0.0026. Key gauging stations in the Carlisle area are Greenholme on the Irthing, Great Corby on the Eden immediately upstream of Carlisle (replacing Warwick Bridge in 1998), and Sheepmount on the Eden downstream of the Caldew confluence. Standby flows (for flood warning) are 400 cumecs at Great Corby and Sheepmount.

A multiple correlation approach relating Sheepmount flows to Great Corby and Greenholme flows provides a reasonable first estimate of Sheepmount flows, although does not predict the rising limb of the hydrograph well, and has some scatter arising from inflows from the Caldew and Petteril and other factors, with possible backwater effects at Greenholme during flood events. Times of travel from Greenholme to Sheepmount average 5.5 hours whilst times from Great Corby to Sheepmount average 3.5 hours. Travel times from Udford+Temple Sowerby to Great Corby are rather more consistent, with a correlation coefficient of 0.95 and mean travel time of 4 hours, but with some underestimation of peak flows and variability in lag times depending on the relative magnitudes and timing of upstream flows. On the Irthing, correlations only have limited success, with a mean lag time from the upper reaches of about 5 hours..

2.4.2 Model Calibration

The River Eden model is the first real time hydrodynamic model to be implemented in North West Region and has been converted from an existing design model. The extent of the real time model is from the Udford and Temple Sowerby gauging stations on the Eamont and Eden to downstream of Carlisle. From Udford and Temple Sowerby, flows are routed using a variable parameter Muskingum Cunge model to the Great Corby gauging station (formerly Warwick Bridge) shortly upstream of the confluence with the river Irthing. Flows are also routed down the Irthing to Greenholme, and through the upper reaches of the Petteril and Caldew tributaries.

The main hydrodynamic model component extends from these locations down to the gauging station at Sheepmount, where the lower boundary of the model is represented by a rating curve. This part of the model extends roughly 3km into the Petteril, 5km into the Caldew, and for the whole river reach from the Irthing/Eden confluence to Sheepmount (with any remaining short reaches infilled by routing models). Tidal influences are not represented. In real time use the model is operated without updating.

Within the main Eden reach of the hydrodynamic model, there are no notable structures and bridges have been modelled by simple Bernoulli losses and weirs as standard broad nosed crested round weirs. There are also several ungauged lateral inflows along the main Eden reach and the tributaries which make a minor contribution to main channel flows. The average channel slope in this reach is approximately 0.0006 and Manning’s n values vary in a range from 0.025 to 0.04 (in bank) and 0.04 to 0.09 (floodplain).

Similar approaches have also been used to model the Petteril and Caldew (e.g. for bridges and weirs). Mean channel slopes are 0.0008 for the Petteril and 0.003 for the Caldew, with Manning n values in the range 0.028-0.035 (in bank) and 0.062 (floodplain) in the Petteril, and 0.035-0.055 (in bank) and 0.045-0.065 (floodplain) in the Caldew. On the Caldew, a minor channel parallel to the main channel (the Little Caldew) is not modelled explicitly.

The model is implemented within a map-based system environment providing displays of instrumentation, floodplain outlines, and point and click displays of observed and forecast river levels and flows. In its current form, the model provides approximately 5-6 hours forecast lead-time in Carlisle.

The model was calibrated using events from Jan 1995, Feb 1995 and Jan 1999 and the following figure shows an example of the model forecasts of levels in Carlisle for the Feb 1995 event.

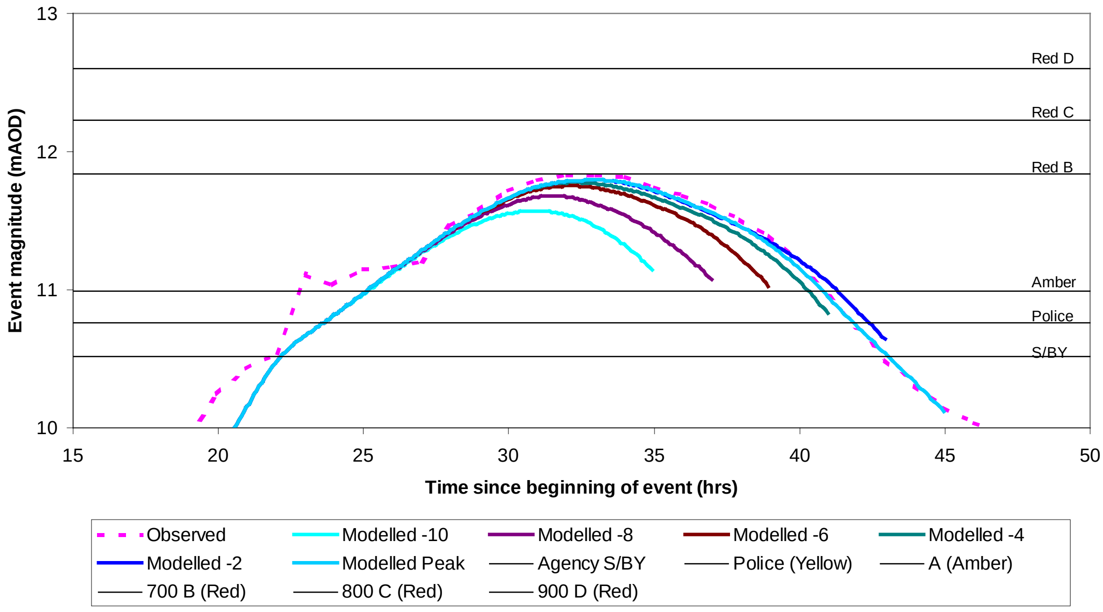


Figure 2.21. Example of fixed origin forecasts in Carlisle for the Feb 1995 event

Possible future developments of the model include use of transfer function rainfall runoff models for the upper Eden and Eamont to further extend lead times, implementation of real time updating of forecasts, and further optimisation of the model, particularly for recession performance. The need for more confidence in high flow ratings has also been identified.

To explore the forecasting performance of the model further, it is convenient to consider the routing and hydrodynamic portions of the model separately, as discussed in the following two sections.

2.4.3 Routing Component

One of the main advantages of hydrological and other non-hydrodynamic routing methods is that no detailed information is required on the channel geometry etc. The model parameters can usually be estimated either from the inflow and outflow hydrographs for the reach or (if no data are available) from rough cross sections through the channel and floodplain at a few locations.

Two key parameters which affect routing performance are the wavespeed and attenuation parameters and the following figures (adapted from Price, 1973) indicate typical values for the Temple Sowerby to Great Corby (formerly Warwick Bridge) reach.

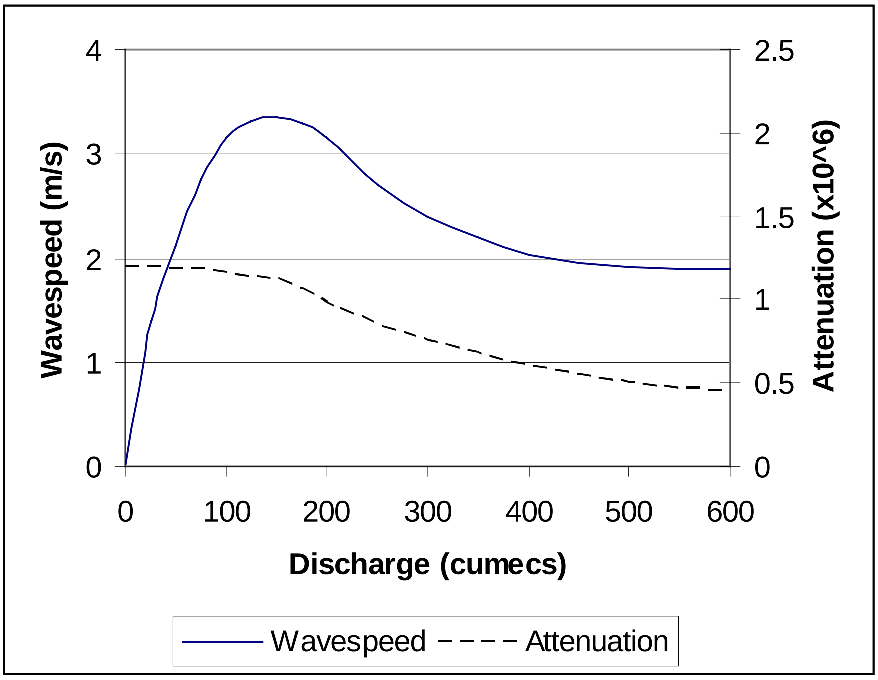


Figure 2.22. Indicative variation in mean wavespeed and attenuation parameter for the Temple Sowerby to Warwick Bridge reach

The real time model includes estimates for these curves at several locations along the reach with maximum wavespeeds typically in the range 2-5m/s for in channel flows.

Some key points to note are that this reach does not have any extensive floodplain (approximately 0.2 km^2/km) and that, at the discharges at which flooding in Carlisle occurs, both the wavespeed and attenuation vary little with flows. FSR studies showed that fixed parameter Muskingum Cunge model worked almost as well as variable parameter versions, except on the rising limb of the hydrograph. Not surprisingly, for peak flows a simple correlation also works reasonably well although with some scatter, particularly at high flows, as indicated by the following figure.

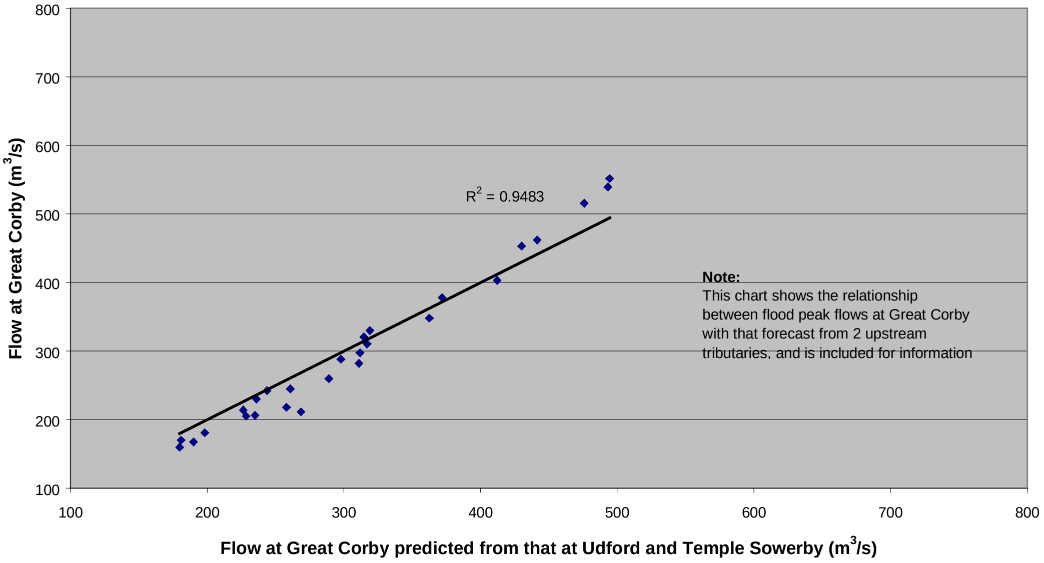


Figure 2.23. Performance of the correlation of Great Corby flows with the sum of Udford and Temple Sowerby flows (from North West Region flood warning procedures)

To explore this behaviour further, and to investigate the impacts of real time updating, it is convenient to calibrate a simple routing model to emulate the behaviour of the VPMC model used operationally. Early FSR studies for this reach showed little discernible difference in estimated peak flows between different routing model formulations (e.g. Muskingum Cunge, variable parameter diffusion), so for these studies a variable parameter kinematic wave model has been used, based on that first proposed by Moore and Jones (1978), and using the simple updating routine outlined in the Todmorden case study.

Figure 2.24 shows some comparisons of performance of this full routing model with the correlation model in the following operational modes; simulation mode, 1 hour ahead without updating, 1 hour ahead with updating. It can be seen that the main differences occur in the rising limb of the hydrograph and in the timing (rather than magnitude) of the peak. In particular, the fixed parameter version predicts too rapid a rise in the early part of the hydrograph, and the correlation model cannot represent the peak flows well.

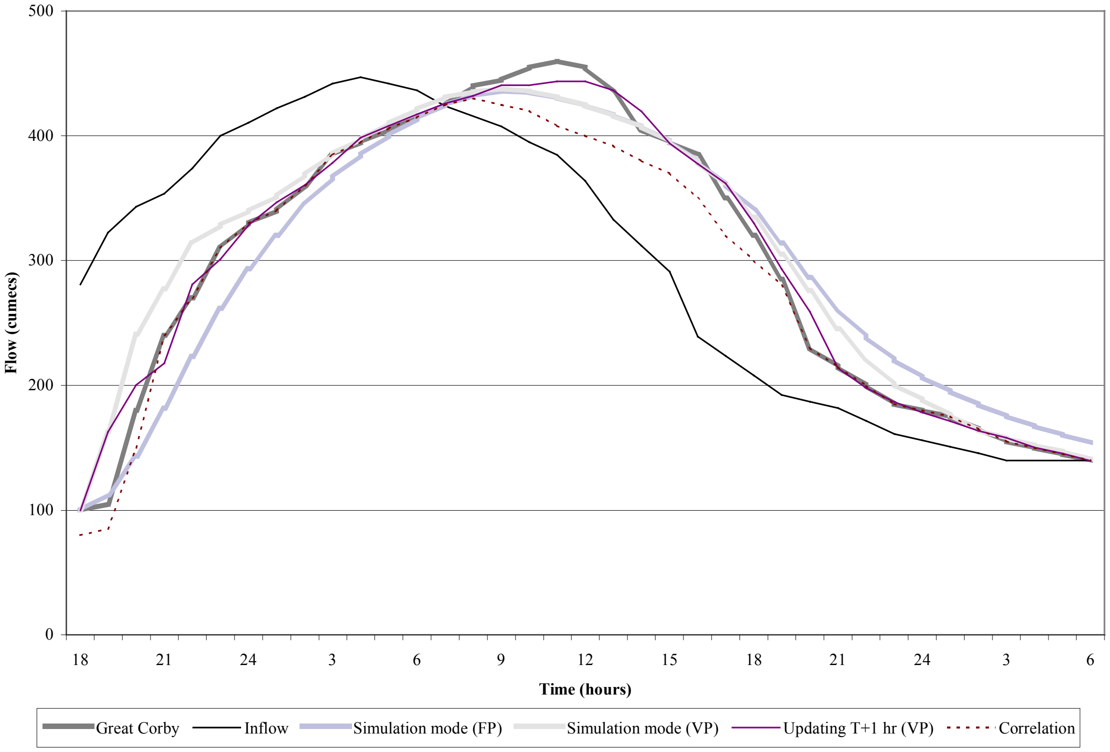


Figure 2.24 Example of routing and correlation model results

Although the model parameters could be tuned further to model this and other events, the main aim of this component of the study was to investigate the sensitivity of the results to variations in input data and the model parameters. For example, uncertainties in input data might arise from doubts about the high flow ends of rating curves, or from errors propagating into the model from a rainfall runoff model immediately upstream. For rating curves, for example, the standard error might be computed at high flows and used as an indication of the uncertainty in the high flow end of the rating curve.

Two scenarios have been investigated: errors in input data in the range -20%, -10%, 0, 10% and 20%, and the same errors in the magnitude of the wavespeed. The results for impact on R^2 and peak flows are shown in the following two figures with and without updating.

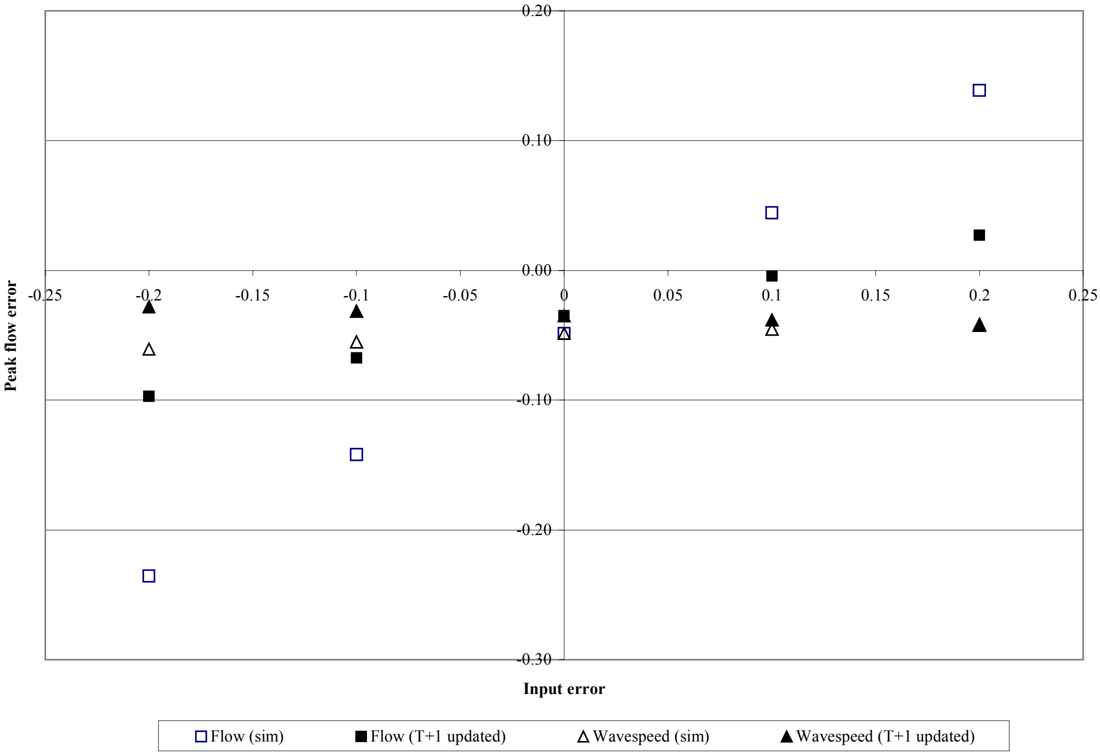


Figure 2.25 Impact of input data and wavespeed errors on peak flows

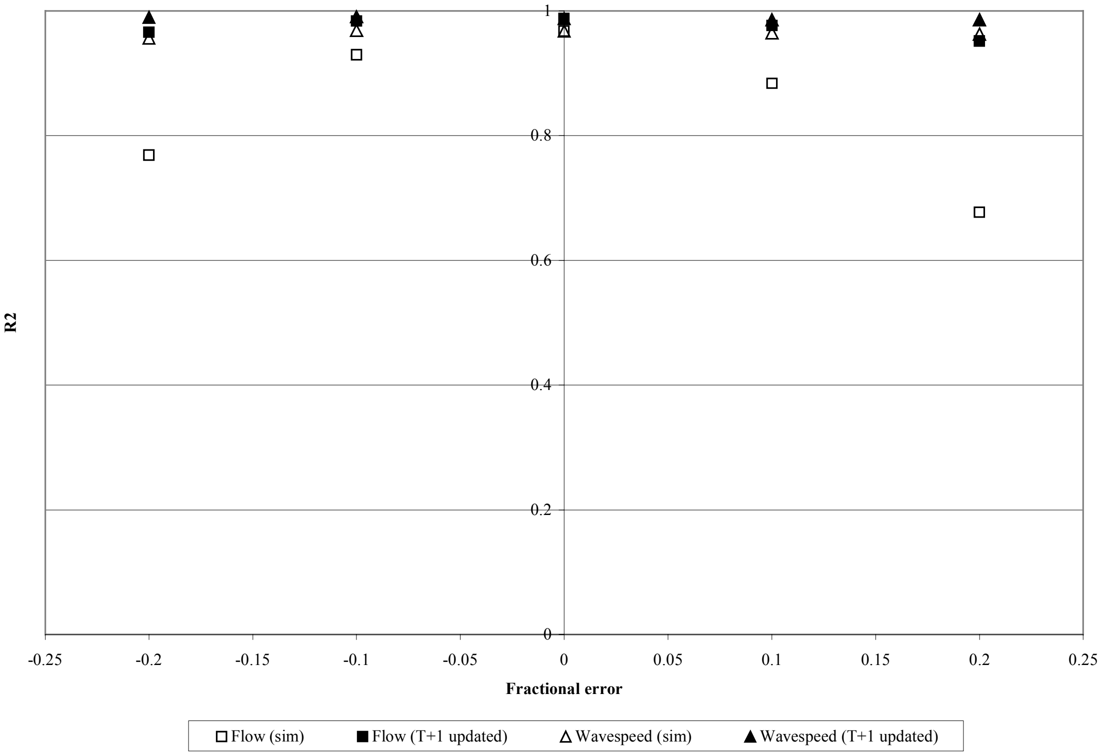


Figure 2.26 Impact of input data and wavespeed errors on R^2

These simulations indicate that the impact on peak flows is roughly linear for errors in input data, but reduced by more than half when updating is used. The model is much less sensitive to the same percentage changes in wavespeed, with an impact of only about 5% on peak flows for a 20% change in wavespeed, and virtually no effect when updating is used (there are of course more proportional impacts on the timing of the peak). For R^2 only the variations in inflows without updating have a major impact, with the other three permutations of input error having a similar effect (however, in this case, this is considered to be an event/model specific result).

2.4.4 Hydrodynamic Component

The hydrodynamic component of the model provides the opportunity to explore several issues relating to high flow estimation near confluences, and the general sensitivity of model output to uncertainties in model parameters (e.g. roughness coefficients) and input data. Also, the model provides a baseline for investigating the performance of simpler correlation models and their limitations when used in river reaches with complicating influences such as confluences.

For the modelling studies, four key sites were selected for output of model performance statistics:

- The node immediately downstream of the confluence of the Irthing and Eden (for convenience called Holmes Gate – which is the nearest settlement to this location)
- The node at the downstream boundary of the model (the upstream face of Sheepmount bridge)
- The node at Club House Bridge on the Petteril within Carlisle
- The node at Caldew Bridge on the Caldew within Carlisle

For model inflows, the design hydrographs developed during the original model calibration were taken as representative of the typical distribution of flows during a high flow event and increases/decreases applied to represent hypotethetical errors arising from errors in the forecast or measured inflow data.

A number of exploratory modelling runs were performed and Table 2.7 summarises the runs for which results are presented later in this section

Table 2.7. Summary of hydrodynamic model runs

Run	Great Corby / Greenholme inflows	Petteril inflows	Caldew inflows	Comments
Baseline				Baseline run for comparison (see Figure 2.27)
Inflows	+10%			Inflows to the model from the Eden, Irthing, Petteril and Caldew changed individually or in combination over the full flow range by varying amounts
	+20%			
		+10%	+10%	
		+20%	+20%	
	-25%		-25%	
	+20%	+20%	+20%	
		+30%	+30%	
	+30%	+30%	+30%	
			-25%	
			-50%	
Timing		+6 hours		Timing of the peak Petteril inflow changed by +6 and +12 hours
		+12 hours		
Parameters				Manning's n changed globally by +10% and -10%

Figure 2.27 shows the hydrographs for the selected model nodes for the baseline event. For this event, within Carlisle, flows on the Petteril peak about 1 hour before the peak is reached at Holmes Gate, and about 7 hours

earlier on the steeper, faster response Caldew. The time of travel from Holmes Gate to Sheepmount is about 4.5 hours according to the model.

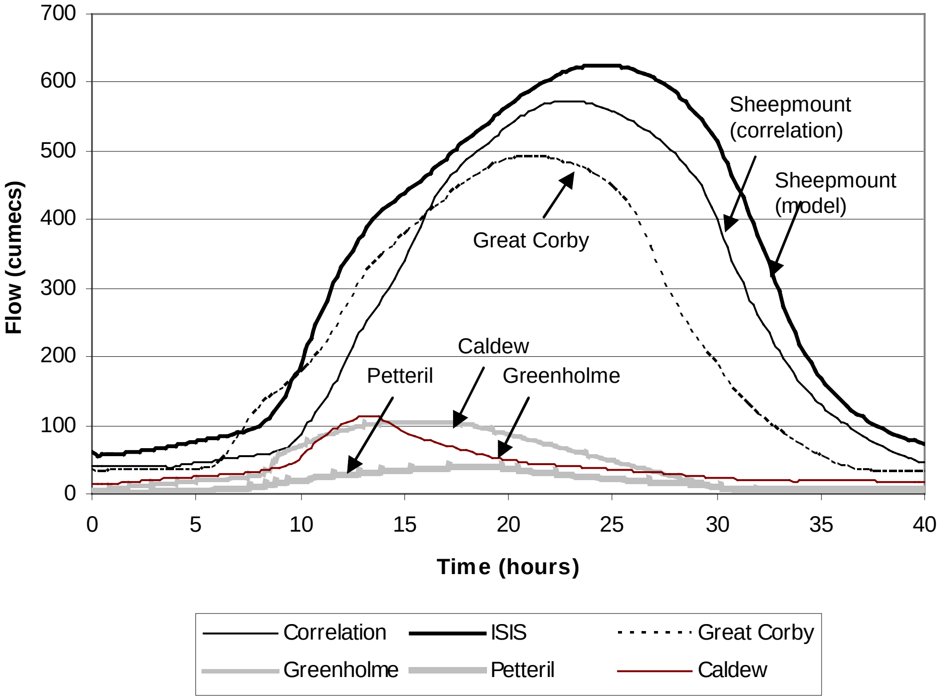
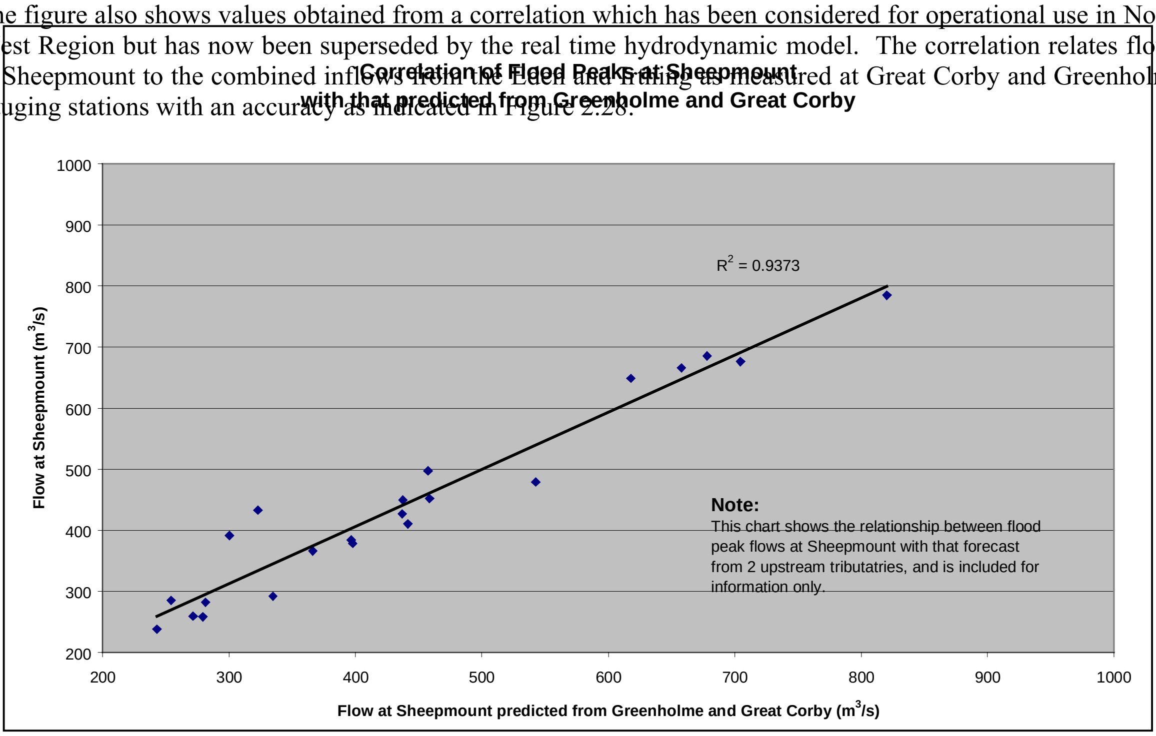


Figure 2.27 Example hydrographs for the baseline case

The figure also shows values obtained from a correlation which has been considered for operational use in North West Region but has now been superseded by the real time hydrodynamic model. The correlation relates flows at Sheepmount to the combined inflows from the Eden and Irthing as measured at Great Corby and Greenholme gauging stations with an accuracy as indicated in Figure 2.28.

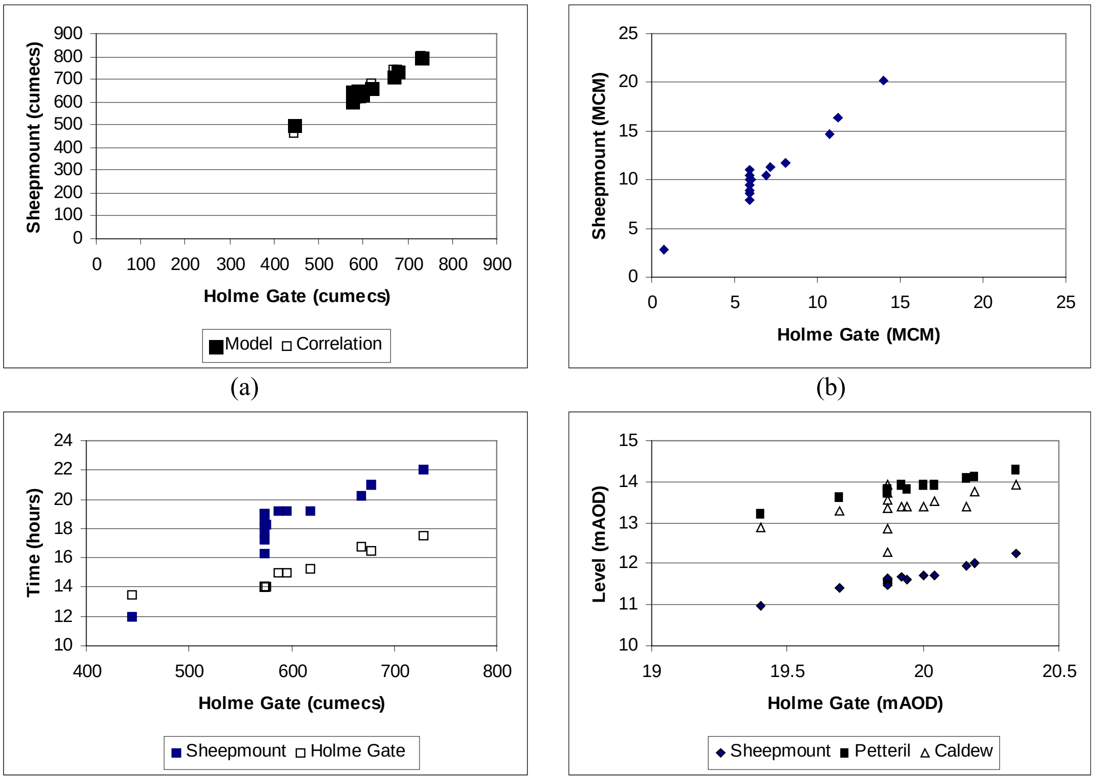


Note: This chart shows the relationship between flood peak flows at Sheepmount with that forecast from 2 upstream tributatries, and is included for information only.

Figure 2.28. Indicative performance of the correlation model

The correlation assumes a mean time of travel of 3.5 hours from the Eden/Irthing confluence to Sheepmount and has an r^2 coefficient of 0.93, although is based on only three years of data. Inflows from the Petteril and Caldew are not accounted for explicitly in the correlation. For the baseline hydrodynamic model analysis (see Figure 2.27), the correlation provides reasonable estimates for both the shape of the hydrograph and the peak flows reached at Sheepmount, although with some underestimation and timing differences. Some other difficulties noted with this approach include the impacts of the Irthing flows typically rising more rapidly than on the upper Eden, variable travel times between the Eden/Irthing confluence and Sheepmount, and variable timing differences between the Eden and Irthing inflows.

When considering the results of the model runs, it is convenient to present results relating to the flows in the main channel (i.e. the Eden) first, and these are summarised in Figure 2.29.



(a) (b)

(c) (d)

Figure 2.29 Examples of hydrodynamic model results for the main river Eden in Carlisle (see text for description)

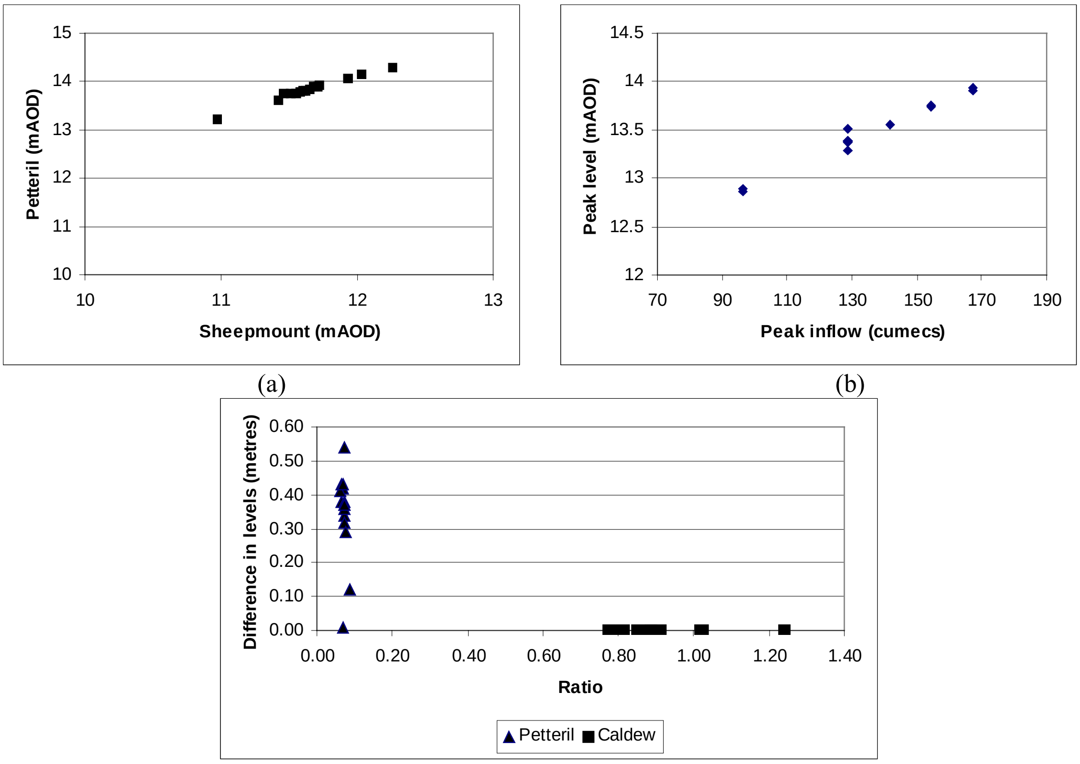
Figure 2.29a compares the peak flows estimated at Sheepmount across all runs with the inflows at Holmes Gate. It can be seen that, despite significant variations in the tributary inflows (see Table 2.7), these do not have a major impact on main channel flows, and a simple flow correlation approach for peaks might be suitable. Indeed, this is confirmed by the open symbols shown on the figure, which are calculated using the multiple correlation shown in Figure 2.28.

A similar correlation based approach also seems a possibility for volumes under the hydrograph (Figure 2.29b), where an arbitrary threshold value of 400 cumecs has been chosen at both sites for these calculations. However, there is more scatter in this relationship, arising primarily for the runs in which the Manning's n coefficient and the inflows for the Caldew were varied i.e. tributary inflows and conveyance have a larger impact on hydrograph shape/volumes than on peaks. This effect is more apparent when comparing the times for which flows remain above the 400 cumecs threshold at both sites as a function of the Holmes Gate inflows (Figure 2.29c). As expected, as inflows increase, the times above the threshold increase, and times are longer at Sheepmount on account of the larger flows and attenuation. However, there is considerably more scatter in this relationship for

Sheepmount flows than Holmes Gate flows, as the shape of the hydograph is affected by tributary inflows etc, particularly on the rising limb, showing that a simple correlation based approach is not so effective when considering flows below the peak value.

The final figure (Figure 2.29d) examines the possibilities for a level based correlation, and shows peak levels at the Sheepmount, Petteril and Caldew sites as a function of Holmes Gate levels. For both the Petteril and Sheepmount, there is clearly a strong relationship with Holmes Gate levels, but there appears to be no unique relationship for the Caldew. Peak levels on the Petteril typically occur within half an hour of those at Sheepmount, and the time of travel from Holmes Gate to Sheepmount is typically 4-5 hours.

The relationships between tributary levels and flows and main channel flows are shown more clearly in the following set of figures.



(a) (b)

(c)

Figure 2.30. Examples of results for the Petteril and Caldew tributaries (see text for description)

The first figure (Figure 2.30a) compares Petteril and Sheepmount peak levels, and confirms the strong relationship between these two sites for a range of combinations of flows in the Eden and Petteril. Thus backwater influences are the main driver for peak levels in the lower Petteril, and for the node selected a simple linear correlation on levels to Sheepmount should be effective for forecasting, assuming a 0-1 hour time difference between the two sites (typically 0.25-0.5 hours).

By contrast, Figure 2.30b shows that peak levels reached on the lower Caldew are little affected by flows or levels in the main Eden, since there is a reasonably consistent relationship between the inflows at the upper end of the Caldew and the peak levels reached within Carlisle. Indeed, the only significant scatter in this relationship arises from the two model runs in which the Manning's n value was varied, affecting the conveyance with an impact of about 0.1m on peak levels for a 10% change in n. Thus a possible forecasting model for the Caldew might consist of a correlation between routed inflows and peak levels with the important proviso that, for the final model run (in which Caldew inflows were reduced by 50%), a second peak arose from backwater effects from the Eden which almost exceeded that from Caldew inflows alone (i.e. this combination of Eden/Caldew flows resulted in significant backwater effects in the Caldew, which were less apparent for the baseline case). There would therefore clearly need to be limitations placed on the correlation in terms of the relative magnitudes of main channel and Caldew inflows.

The final figure (Figure 2.30c) summarises the essential difference between the Petteril and Caldew response by comparing the differences between peak levels reached, and the levels at the time of maximum flow, in the two tributaries. For the Caldew, the two estimates for levels are usually almost the same, whereas there is a wide variation between runs for the Petteril (due to the lack of a unique relationship between levels and flows). On this plot, the horizontal axis is plotted in terms of the non-dimensional distance from the Eden confluence, given by L/L_b, where L is the distance of the node from the confluence, and L_b is a measure of the backwater length in the channel, given by $L_b=H/s$, where H is the river depth at the confluence, and s the slope of the river bed in the tributary. Plots of this type could be possibly be produced for a range of node locations, and combinations of tributary and main channel flows, to provide an indication of the conditions at which any given location is affected by backwater, and where a level correlation would be more appropriate than a flow-based correlation. A further refinement would be to plot the level difference in terms of the difference with peak levels reached in the main channel at the confluence, and the peak level reached in the tributary, although this has not been attempted here.

2.4.5 Conclusions

The modelling studies for the Eden have suggested the following general results which might be applied to other catchments with simple routing problems (i.e. floodplains but no artificial influences) and confluence flooding:

For the routing component

- The structure of fixed parameter routing models is such that error propagation is linear in simulation mode i.e. a given error in input flows translates to the same error in output flows
- For variable parameter versions, in this case despite the presence of a limited floodplain, at the flows at which flooding occurs the variation in wavespeed and attenuation parameters with flow is small, leading again to an almost linear response to input data errors (which might themselves arise from errors in the high flow ends of rating curves, or errors in flows forecast by rainfall runoff models). Comparable percentage errors in model parameters (e.g. wavespeed) have a relatively small effect for this model.
- Even with the simple updating routine used, updating can dramatically reduce the influence of input data errors, in this case reducing errors in estimated flows by a factor of four.
- For this simple river reach, a flow correlation appears to work well for peak flows, but as is common this approach works less well for the rising limb of the hydrograph.

For the hydrodynamic model

- The case study has illustrated how a hydrodynamic model can be used to map out the behaviour of flows and levels at key sites within a Flood Warning Area and so develop simpler local forecasting models. These could either be used as a stop gap, in advance of development of a real time hydrodynamic model, or as a backup to a more sophisticated model.
- Results are very site specific and will depend on the channel configuration, location in the channel, structures etc in the model. For this case study, for one of the key sites (on the Petteril), backwater influences dominated so a simple level correlation with time difference model could be used to forecast peak levels at that point, whilst for the other two sites (Sheepmount, Caldew), inflows dominate the response so a peak flow correlation with time lag would be used (multiple correlation for Sheepmount, single correlation for the Caldew).

- If correlations are to be used, the hydrodynamic model can also be used to map out limitations on the results; for example, ranges of flows in which the results are valid, and outside which the assumptions break down (e.g. the assumption of no backwater effects for the Caldew site, impacts of tributary inflows). For sites at which flow correlations work, then error propagation can be expected to be roughly linear in terms of peak flows.

- Errors in rating curves can affect model accuracy in several ways. If the rating appears as a downstream boundary, then for this model there appeared to be little impact of rating errors on flows and levels further upstream. However, if the rating is used to estimate inflows to the model from telemetered levels, then the rating error leads to a corresponding inflow error. Similarly, for sites which use a flow correlation forecasting method, a rating is required to estimate levels at the site introducing an additional source of error (which could be parameterised, for example, via the standard error in the rating, if based on discharge measurements).

- Although peak level and flow correlations appear to work well in some situations, the modelling studies confirm the poor performance of correlations on the rising limb of the hydrograph, meaning that they are less suitable for estimating the volume or time spent above thresholds, or the times of crossing thresholds.

- Uncertainties arising from model parameters (e.g Manning’s n) are generally much smaller than those arising from timing and magnitude errors in main channel and tributary inflows. In this case, the impact of a 10% change in n was typically less than 0.1m in levels. Most Section 105 reports include sensitivity studies of this type (providing a ready made assessment of this source of uncertainty), and an R&D project “Reducing uncertainty in river flood conveyance” is specifically examining uncertainty arising from roughness parameterisations and reports in 2004.

- For sites dominated by backwater effects, non dimensional plots of the type shown in Figure 2.30c provide a possible basis for summarising results for a tributary, allowing the extent of backwater effects to be estimated for different combinations of tributary inflows and main channel flows (both timing and magnitude effects).

3. SUMMARY OF MAIN FINDINGS

3.1 Introduction

Through literature reviews, reviews of Agency practice, and exploratory modelling studies, the previous two sections have considered a number of issues which are relevant to Real Time Modelling in the Agency. These include:

- The indicative accuracy of models generally and in Agency use
- Methods for evaluating model performance
- Methods for evaluating overall forecasting system performance
- Approaches to dealing with uncertainty
- How errors in data, forecasts etc propagate through to flow forecasts
- Current active research areas in Real Time Modelling
- Future R&D needs (improvement plans)

The aim of this section is to review the main findings from these studies and to indicate how these results have either been applied in the guideline document, or used to inform the recommendations for future R&D proposals.

The following sections summarise the main conclusions for the categories of model defined in Part A which are currently in operational use within the Agency (Section 3.2) and conclusions regarding a range of other issues such as post event analysis and error propagation (Section 3.3):

3.2 Accuracy of Models

3.2.1 Empirical Models

For quantitative flood forecasts, correlations are the main type of empirical model used in real time. Experience with correlation based approaches within the Agency shows that:

- For simple river reaches, with no floodplain or major tributary inflows, correlation coefficients of more than 0.9 are often reported but performance is often worse if there are complicating effects such as floodplains, storm size/location, effects, or major tributary inflows
- The accuracy of a correlation based approach is entirely site and data dependent and cannot be predicted without exploratory modelling studies
- Models calibrated on peaks often provide a poor representation of the full hydrograph (particularly the rising limb which relates to the timing of crossing of trigger levels)
- Correlations provide an excellent backup to more sophisticated models (and are used in this way in Midlands Region, for example)
- Correlations based on flows are more likely to provide consistent performance over time than correlations based on levels (but require a rating curve at each station)
- The Eden case study also illustrates how correlations might be used for local estimates of levels and flows within a flood warning area in the absence of (or in advance of commissioning) a real time hydrodynamic model.

The propagation of errors is necessarily linear for this type of model since the model itself is linear and updating is not used.

3.2.2 Black Box Models

There have been many research studies into the performance of transfer function models and, for fast response catchments, results can be comparable to those obtained with a conceptual rainfall runoff model, all other factors being equal (accuracy of data, skill of model developers etc). Within the Agency, this type of model is currently used in Southern, North West and South West Regions, and was formerly used in Anglian Region. Error propagation studies suggest a linear response when using total rainfall in simulation mode, with a greatly reduced sensitivity to rainfall when updating is used. The main issues regarding future uses of these models within the Agency include:

- Further investigation into the need for, and recommended types, of effective rainfall formulation under flood event conditions
- Developing consistent, automated ways of updating forecasts in real time based on antecedent/current conditions/smoothed versions of the observed flows
- Evaluation and use of new model structures (more parsimonious, parallel pathway etc)
- Appropriate model calibration criteria for flood forecasting applications (values over threshold etc)
- Choosing between use of radar actuals and forecasts or raingauge data in forecasting
- Choice of appropriate timesteps to fully resolve the rising limb of the hydrograph

The National Flood Forecasting Users Group has identified a need for additional R&D to develop more consistency in the use and application of these models for Real Time Modelling within the Agency and that recommendation is fully supported by this project. A number of other blackbox modelling approaches have also been considered/evaluated as part of Agency R&D projects and may merit a separate project on evaluation of new rainfall runoff modelling approaches (neural networks, fuzzy logic, nearest neighbour etc; see Part C)

3.2.3 Conceptual Models

Conceptual rainfall runoff models are currently used for flood forecasting in Thames, North East, Midlands, Anglian Regions. In simulation mode, for small fast response catchments, a well calibrated model (using good quality data etc) can typically estimate peak flows to within 10-30% across many events, and with an R^2 of 0.8 or better. On fast response catchments, models of this type can amplify errors in rainfall, but also in some cases reduce errors, and updating can considerably improve the accuracy of forecasts, although results are very model specific (particularly for state and parameter updating, which are integral to the model ‘brand’). Due to the conceptual nature of these models, the decision whether to use semi distributed or lumped models should depend more on whether there is a consistent relationship between rainfall and runoff in a catchment rather than a detailed analysis of soil types, vegetation, geology etc. For the Todmorden case study, a roughly linear response seemed typical for rainfall events of the magnitude likely to cause flooding, and this may be typical of other fast response catchments under saturated conditions. Recent research and other studies have suggested that further improvements are desirable in the areas of:

- Conceptual modelling of groundwater dominated flooding making use of real time well level and pumping/abstraction data
- Fully distributed models to make use of the latest high resolution (Nimrod) and soil moisture data (MOSES), particularly for urban catchments
- Extending lead times for fast response catchments using ‘first alert’ systems based on rainfall measurements and forecasts, conceptual model runoff forecasts based on rainfall forecasts, pattern recognition of storm types/antecedent conditions etc which may lead to flooding

Conceptual models are also a prime candidate for real time modelling of flood flows from ungauged catchments (particularly low benefit locations) but this is not recommended at present due to the uncertainties in regionalising parameter values (an active research area) and, by definition, the inability to update forecasts in real time. However, current research into continuous simulation modelling and “the revitalisation of the FSR/FEH rainfall runoff method” R&D project may lead to useful results for real time application (although this would require additional R&D to determine the operational benefits).

3.2.4 Routing methods

When considering model performance, it is convenient to discuss all types of routing models together since there are many similarities between the different types of models. Early studies during preparation of the Flood Studies Report indicated that, for a simple channel with a floodplain but no artificial influences, there is little to choose between fixed and variable parameter routing models in terms of predicting peak flows, but that variable parameter models perform better on the rising limb of the hydrograph (and hence in forecasting volumes and the crossing of threshold levels). Peak flow accuracies within 10% were usually achievable with these models and these results applied on rivers with mean slopes as small as 0.001. However, models of this type cannot represent effects arising from the upstream movement of waves; for example from tidal effects or structures. Research on model structures and solution procedures has continued since that time and the most recent DEFRA funded research has shown that there are some numerical issues with the more complex routing models (oscillations, lack of volume conservation etc) when used in compound channels which can be greatly reduced through choice of an appropriate computational scheme. In the simpler models, error propagation is roughly linear, although greatly reduced by updating, and, even for variable parameter versions, under flood conditions the rate of change of parameter values can be small, giving a similar response (but exploratory modelling studies are required to confirm this).

3.2.5 Hydrodynamic models

For hydrodynamic models, recent review and R&D studies have shown that the following indicative accuracies should be achievable with a properly structured and calibrated model in UK conditions in simulation mode (e.g. Samuels, 1995; Environment Agency, 1997; Ramsbottom *et al*., 2000; Section 105 studies):

- Topographic errors – errors in levels of 0.1-0.3 m
- Model calibration issues – error in levels of 0.15 m within the range of calibration (more outside)
- Rating equation uncertainty at high flows – error in levels of 0.2-0.5 m
- Additive errors – up to 0.75 m (assuming all other errors statistically independent)

This type of thinking about model accuracy is only now making it through to design/simulation mode (see Environment Agency, 2001e) studies and has barely been considered for real time application. Also, in real time use, two competing effects which are worthy of further investigation are:

- Updating has the potential to reduce errors, but is considerably more complicated to apply than for rainfall runoff and simpler routing models since several updating sites need to be considered jointly, and state and parameter updating schemes must be applied in a physically realistic way whilst maintaining model stability and accuracy
- For real time use, the model may need to be ‘slimmed down’ or otherwise simplified for reasons of stability or to increase run times.

3.3 Other Issues

3.3.1 Model Uncertainty

For Real Time Modelling, the term ‘uncertainty’ expresses the lack of certainty in a model’s output due to errors in input data, model structure, model parameters etc. Uncertainty can be greatly reduced by use of an appropriate type and structure of model for a given modelling situation, by ensuring that only reliable real time data are used, and through appropriate use of real time updating of forecasts.

Uncertainty can be diagnosed both off-line and in real time. The case studies illustrate some simple approaches to off-line diagnosis of uncertainty with respect to model parameters and input data, and more sophisticated approaches have been reported in the scientific literature (see Section 1), including investigating factors such as parameter interdependence and stochastic sampling of response to variations in both input data and parameters.

Regarding real time diagnosis of uncertainty, within the Agency this is presently limited to the use of 'what if' scenarios but recent developments mean that a step change in approach should be technically possible, if this is required. Ingredients of this approach would include real time diagnosis of uncertainty for each of the main components of the forecasting problem, which can include rainfall forecasts, rainfall actuals, rainfall runoff models, routing models, rating equations etc, and including different approaches to model updating. Some possible R&D and other projects which may help to develop such an approach could include:

- Operational implementation of the outputs from the R&D project "Diagnosis and real time reporting of uncertainty in Nimrod data and forecasts"
- Statistical and pattern recognition methods for predicting future rainfall in real time based on historical combinations of catchment conditions and storm types (see Section 1)
- Using the probabilistic outputs from the CDP ("Convection Diagnosis Project") in real time and, for the future, probabilistic Nimrod outputs
- Real time sampling of model outputs for different probability distributions of model parameters computed off line using stochastic sampling techniques, including multiple objective criteria
- Making use of the outcome of R&D project "Reducing uncertainty in river flood conveyance" (2002-04) for which component T6 aims to develop a tool for estimating uncertainty in conveyance due to roughness estimates, modelling assumptions etc.

The result from such an approach would be an ensemble (probabilistic) level or flow forecast at each Forecasting Point, which could be expressed as a probability distribution or using error bars, confidence limits etc (Figure 3.1) Any such study would also need to consider the operational and procedural issues in presenting forecasts to flood forecasting staff and in interpreting probabilistic forecasts as a basis for issuing flood warnings.

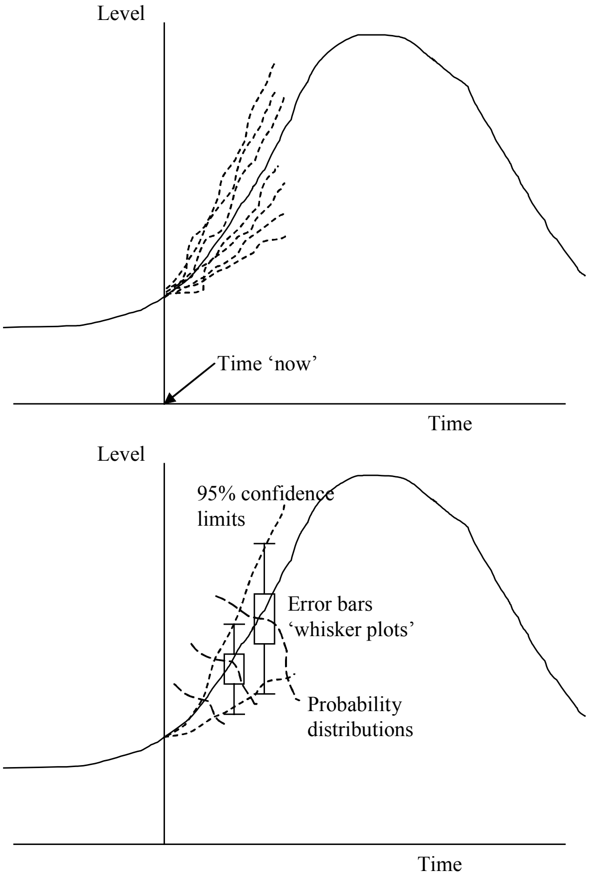


Figure 3.1. Three possible ways of displaying uncertainty in real time (top figure-stochastic model runs, lower figure-confidence limits, error bars, probability distributions; note that in practice only 1 or 2 measures would be used on the same figure)

3.3.2 Post Event Analysis Techniques

Although case studies of the type outlined in this report can be useful, a comprehensive investigation would require a post-event (or uncertainty) database, containing the outputs from many types of model, at many sites in all Regions, for many different types of catchment/forecasting problem, and including examples of the main categories of flood generating event (frontal rainfall, snowmelt, convective storms etc). However, this project has shown that post event analysis is only performed in some Regions at present, and often concerns the performance of the whole forecasting system (including dissemination), not just the Real Time Modelling components.

One of the objectives of the present project was to review and evaluate techniques for post event evaluation with a view to making a start towards establishing some standard approaches within the Agency. Section 1.6.5 summarises the main outcome from this work but, in brief, the following types of graphical and tabulated output are recommended as a starting point:

- Post event reporting – Fixed lead time comparisons, Critical Success Index, R^2 statistics
- High level targets – Histograms of minimum warning time, tabulated CSI and minimum warning time values by river reach, qualitative scoring of compliance with targets
- Model performance – Fixed lead time values for the R^2 statistic and CSI vs lead time, peak magnitude and timing errors vs flow, standard deviation of the estimates (e.g. accuracy ellipses)

together with the following general conclusions regarding measures for calibrating models and evaluating model performance:

- For flood forecasting applications, no one statistic gives an overall view of model performance, so a range of measures should be used (peak, full hydrograph, values above a threshold etc)
- Normalised values should be used for comparisons between sites/models etc
- Threshold exceedance statistics are useful (e.g. CSI) and focus on the success of the model at forecasting high flows
- Real time updating and event magnitudes can have a crucial impact on performance and the method used should be quoted with any performance statistics including stating the fixed lead times used

Although Section 1 recommends a range of post event analysis techniques which might be adopted as standard within the Agency, there is clearly scope for additional R&D (or projects) into specifying nationally consistent ways of analysing and presenting results on model performance, and development of detailed specifications for automated tools for performing this type of analysis.

3.3.3 Error Propagation in Models

The review and exploratory modelling studies show a complicated picture for the propagation of data and other errors into model results, meriting further research in conjunction with studies on incorporating model uncertainty into real time forecasts (see earlier). The literature in particular reports a range of results from data errors being greatly magnified by some types of model, and almost damped out by others. However, many of these previous studies have applied to simulation mode and do not include the influence of real time updating on the results.

Despite these difficulties, the exploratory modelling studies (see Section 2) have made some progress in quantifying the nature of error propagation in some simpler but common modelling situations; for example, a lumped rainfall runoff model on a fast response catchment, or a routing or hydrodynamic model used on a single river reach with no artificial influences. These results typically show a roughly linear response under flood flow conditions arising from factors such as the limited infiltration which occurs around the peak (due to saturated catchment conditions), and the lack of flow dependence of model parameters (such as wavespeed or attenuation in routing models). However, these results are site and model specific.

The results also necessarily apply to the model's representation of flood flows rather than being based on actual catchment response, and it is worth noting that many of the simpler models used within the Agency are intrinsically linear, including unit hydrograph and transfer function models (when using total rainfall), and some fixed parameter routing models. Research studies have also on many occasions highlighted the general similarity/equivalence between models such as the fast response pathway in conceptual models, simpler transfer function models, Muskingum-type routing models, multiple correlations, and error prediction routines, when expressed in finite difference form.

Perhaps the most important point to note is that, despite some findings in the literature, errors in input data are not necessarily increased when feeding through a rainfall runoff or routing model, and in some cases some aspects of the model performance may improve at the expense of others (e.g. improved estimates of peaks but a worse R^2). Also, updating can play a key role in reducing errors at short lead times, often more than halving errors in peak flows. On more complex catchments, a number of other factors might also lead to damping out of errors in flood flow conditions, including the impact of permanent losses from the system during the flood event (e.g. washlands, spill over embankments, pumping) and the natural 'smearing' of errors arising from timing and magnitude differences when there are several tributary inflows. However, a comprehensive post event database would be required to investigate the full range of modelling situations within the Agency.

3.3.4 Guideline Recommendations

This chapter has outlined a wide range of research and modelling results but, for the guideline document, a more concise format was required, and a range of presentation methods were considered, including flowcharts, decision matrices, and tabulations.

Regarding conclusions on model accuracy and uncertainty, a mixture of qualitative and quantitative assessments is presented. In the main body of the guidelines, for consistency with project W5/010 (Environment Agency, 2001b), a three value scoring system has been adopted to indicate the relative accuracy of each approach in a given situation (1=low, 2=medium, 3=high) as indicated in the following sample:

Table 3.1. Potential Accuracy Scores for different types of catchment forecasting problem (abbreviated version)

Issue	Flood Watch contingency table	Correlation (M = multiple)	Time of travel maps	Transfer function models (N=non linear)	Conceptual models	Hydrological routing (V=variable parameter)	Kinematic routing (V=variable parameter)	Hydrodynamic routing
Rainfall runoff issues								
Fast response catchment				3	3			
Floods can occur from a permeable or dry catchment		1		2-3N	3			
Flood response can vary depending on spatial variations in rainfall		1		2-3	2-3			
…..continued								

For quantitative estimates of accuracy, readers are referred to the present report for detailed information on the likely performance of different categories of model in simulation mode. However, based on the modelling studies in this report, the approach described in Section 1.8 has been offered as a possible way of thinking about the relative magnitude of the various errors and uncertainties and how they propagate through to errors or uncertainties in forecasts of levels. Although the final results are only indicative, they may be useful in focussing attention on the aspects of a model which generate the largest uncertainty.

PART C - IMPROVEMENT PLANS

Apart from preparation of the "Guidelines on Real Time Modelling", the other main objective of this component of the project was to identify possible improvement plans for Real Time Modelling in the form of one page outline (DEFRA/EA Form A) R&D proposals. Topics for consideration included:

- Gaps in the existing research base
- Opportunities stemming from emerging technologies
- Short term improvements

Part C outlines the process by which possible projects were identified and summarises the scope of the projects which were finally selected.

1. IDENTIFICATION OF R&D PRIORITIES

1.1 Previous recommendations in this project

During the early stages of this project, a review of current forecasting problems within the Agency, and of existing real time modelling techniques in the UK and internationally, led to a list of 7 potential projects as indicated in Table 1.1. These projects have been retained in the final list although in a slightly improved form.

A similar review as part of the Rainfall Measurement and Forecasting component of this project (Environment Agency, 2002a) led to a set of 33 proposed projects, from which 12 were selected for further consideration as being of high priority, but presently not being funded from other sources. This second set of projects mainly concerned improved techniques for rainfall measurement and forecasting but inevitably there was some overlap with the Real Time Modelling component and the following proposed projects fell into that category:

- Propagation of errors in rainfall forecasts into flood forecasts
- Training tools and decision support systems
- Use of MOSES for flood forecasting applications
- Using Heavy Rainfall Warnings in flood forecasting
- Using ensemble forecasts (i.e. rainfall forecasts)
- Assessment of Nimrod forecasts for Real Time Modelling

The following projects were also scored as high priority but were assumed to be going ahead already:

- Improved techniques for local adjustment of weather radar data
- Diagnosis and real time reporting of uncertainty in Nimrod data and forecasts
- Storm scale numerical modelling
- Comparative study of MOSES and MORECS
- First guess heavy rainfall warnings/extreme event warnings
- Hardware/software/archiving improvements to radar network
- GANDOLF/CDP into Nimrod

These projects are discussed further in the Technical Report for the "Rainfall Measurement and Forecasting" component of the project.

Table 1.1. Potential new R&D projects identified in the early phases of the project

Project	Description
Generic characterisation of effective rainfall	The estimation of effective rainfall from total rainfall is fundamental to most rainfall runoff models. At present, no consistent approach exists for defining effective rainfall and research is required to explore whether generalised non-linear relationships can be developed for a range of different catchment types (as a function of soil composition?) and a range of antecedent conditions. A standard set of non-linear filters that could be used as an 'off-the-shelf' real time tool would improve forecast quality and consistency.
Best practice in transfer function rainfall runoff modelling	Although transfer function models in various guises have been used by the Agency (and SEPA) in the last twenty years, the structure, identification, calibration and application of the models varies greatly. Research is required to identify best practice in terms of transfer function model structure, calibration (including parameter estimation algorithms), input data (total rainfall or effective rainfall), and updating methods (state and parameter). An objective inter-comparison on test catchments is suggested as a suitable way forward.
Neural network modelling	The Agency has funded a limited amount of research into the development of the application of neural network modelling for real time flood forecasting. However, additional work is required to identify appropriate areas of application for the technology, and to further develop the considerable knowledge that already exists and to apply it in England and Wales.
Parameter updating in real time hydrodynamic models	Research would be useful on the use of real time parameter updating in one-dimensional hydrodynamic models. This requires, specifically, research into the use of updating factors such as Manning's *n* values on a seasonal basis, reducing culvert capacity to simulate blockage or updating weir coefficients to simulate crest blockage. At present very little is known about the possible uses of these approaches in real time modelling and further research into their application is required.
Loss models in unit hydrograph techniques	Many unit hydrograph models have only a small set of parameters e.g. time to peak, peak flow, duration and a loss term. The loss term, representing the losses to groundwater, evaporation etc, is the one which is most difficult to define and many different parameterisations have been suggested e.g. a constant percentage of runoff. However, possibly more sophisticated representations are more appropriate for real time flood forecasting applications.
Accuracy, Reliability and Timelines requirements	The Concerted Action Workshop (Environment Agency, 2000b) proposed some tentative estimates for High Level Targets for flood warning within the Agency but recognised that further work was needed. While the project aims to treat these criteria in relation to forecasting, it points out the interfaces with the other flood forecasting and warning processes. It is recommended that the National Flood Warning Centre takes the whole process on board under the umbrella of one R&D project to specifically examine possible gaps in the estimation of these performance criteria.
Post event database	At present there is no standard approach to post event analysis of model performance and no national or regional databases to support such analyses. This means that it is a time consuming and difficult task for operational staff to evaluate model performance (as a basis for future improvements), and R&D studies such as this one need to physically obtain the models used (and possibly recalibrate them) and to reconstruct forecasts as best as possible based on the data which was archived during (and after) the event. This necessarily restricts the quality and breadth of analyses which can be performed. Research is required into the information which should be archived and on how it can be analysed and presented.

1.2 Findings from other Projects

Since the initial work on this project, work on preparing the "Guidelines on Real Time Modelling" and further literature reviews have led to identification of 4 additional projects. However, it is perhaps useful to give a quick guide to recent Agency and other thinking on R&D needs as identified from the following sources (note that, to keep the description short, topics are combined, or paraphrased, in some cases, and only topics related to Real Time Modelling are mentioned):

a) R&D project 252 (National Rivers Authority, 1993)

This study reviewed the performance of three operational models on nine catchments in Thames Region using raingauge, radar and rainfall forecasts. Topics identified as requiring further research and development included:

- Modelling of large catchments using network models, possibly supported by digital terrain and distributed land use datasets
- Improved conceptual rainfall runoff models for catchments where surface/groundwater interactions and pumped abstractions are important.
- Development of state correction schemes for hydrological channel routing models either in isolation or when used as part of a rainfall runoff formulation.
- Evaluation of simple lumped conceptual rainfall runoff models against more distributed models which use radar grid data and digital terrain and land use datasets, for operational flood forecasting
- Development of improved measures of forecast performance, which take into account their use in issuing flood warnings
- Development of decision support procedures for issuing flood warnings, given uncertain rainfall and flow forecasts

b) R&D project 433 (National Rivers Authority, 1995a)

This project reviewed the accuracy of flood forecasting techniques used in the England and Wales and overseas up to the mid 1990s. Topics identified as requiring further research and development included:

- Adoption of a systematic and uniform practice for post event forecast evaluation in all regions
- Identification of the optimal flood forecasting strategy based on response times and storm types
- Identification of optimal flood forecasting strategy for a specific site
- Integration of routing and rainfall runoff models
- Use of real time updating
- Providing an ensemble of forecasts
- Use of fully distributed models
- Monitor developments in Numerical Weather Prediction on hydrological scale

although the projects were not scoped out in any more detail.

c) The RIBAMOD project (Casale et al., 1997)

It is perhaps also helpful to obtain a wider perspective on research needs and this European Union funded project which has been running since 1996 has the following objectives:

- The integration of meteorological forecasts into real time flood forecasting systems
- Remotely sensed information assimilation within flood forecasting systems
- Real time flood management
- Operational experience of flood real time forecasting and warning
- Role of meteorological modelling and weather analysis for precipitation and flood forecasting
- Rainfall measurement and hydrological modelling for flood forecasting
- Research needs for improving the reliability of forecasting and warning systems

A 1997 workshop on "Integrated systems for real time flood forecasting and warning" gives an idea of some of the areas identified as priorities for Real Time Modelling by participants in this project; including the need to:

- Plan more effective use of flood storage in major events requiring long lead time forecasts
- Develop methods for disaggregating of spatial and temporal rainfall fields to use data from meteorological forecasts in flood forecasting at the catchment scale
- Balance sophistication of the components of a real time forecasting system
- Identify hydrological and meteorological conditions (like basin scale, storm size etc) which favour the use of distributed and semi distributed instead of lumped models
- Determine the minimum number of observation points for rainfall in a catchment for flood forecasting
- Develop decision support systems for flood control rooms
- Develop clear objectives for the performance of the flood warning system e.g. no loss of life, 80% Reliability etc
- Quantify and reduce the uncertainty in real time precipitation forecasts
- Express flood forecasts (flow and level) in a probabilistic way with uncertainty bands rather than as specific values
- Account for the antecedent state of the catchment
- Develop ways of matching flood forecasting models to the catchment – there is no universal model
- Recognise and predict rare and exceptional events

d) Concerted Action Workshop for Flood Forecasting and Warning (Environment Agency, 2000b)

This workshop was held in February 1999 following the 1998 floods and aimed to examine the needs for research into several areas linked to flood forecasting and warning, including detection, forecasting, dissemination and social response. Participants included representatives from the Agency, the Met Office, MAFF, and universities and research centres. The workshop report also included reviews of past and present R&D in flood warning within the Agency, and of future needs. For Real Time Modelling, some of the topics identified where knowledge was lacking were (in abbreviated form):

Detection

- Detecting floods in small catchments
- Refinement of MORECS
- Telemetry operation in extreme events
- Link between antecedent wetness and effective rainfall
- Use of probabilistic forecasts

Real Time Modelling techniques

- identification and development of performance measures and consistency of application
- the need to undertake post event reviews
- development of probabilistic forecasts that are more accurate to reduce the risks associated with forecasting data error bands
- forecasting between points and transfer to points downstream
- dealing with uncertainties of forecasting in real time, missing data and development of scenarios
- use of simple modelling techniques to give indication of alert status based on an ensemble of weather forecasts and antecedent conditions
- development of improved level-flow relationships and the need for good quality high flow data in extreme events
- development of updating techniques to minimise model uncertainties
- assessing the influence of rainfall and catchment wetness
- development of flexible models to enable the development of evolutionary modular toolkits
- the need to be able to model extreme scenarios and to identify conditions leading to extreme events
- development of decision support systems and a technical toolkit of best practice
- forecasting in ungauged "flashy" catchments

- determining the optimum target service levels for the public, emergency organisations and Agency staff to ensure that flood warnings are effective taking into account the types of catchment where the greatest flood risks exist
- review and benchmarking of models
- coupling of meteorological and hydrological models and improved reliability of rainfall runoff and hydraulic modelling, particularly under extreme conditions
- Model structures for extreme fluvial events
- impacts of climate change

e) Good Practice Baseline Review (Environment Agency, 2000a)

This review (and the post Autumn 2000 floods update) aimed to review current best practice within the Agency in a number of areas relating to flood warning including detection, real time modelling, dissemination of warnings and operational procedures etc. Regarding fluvial Real Time Modelling, the main issues which were raised as having no satisfactory 'best practice' at present (and requiring future research) were:

- Data from all events to be stored to a nationally agreed format so that it may be easily retrieved, manipulated and presented
- Quantitative use of radar data in forecasting models has been recognised by NWRS and the existing R&D programme as needing improvement
- Systems for detecting and tracking of thunderstorms recognised as needing further development
- Real time measurement of catchment wetness – no region does this at present
- Forecasting models for steep fast response catchments
- Forecasting/warning method for unusual events (dam break, reservoir overtopping)
- Forecasting method for flooding from groundwater (example quoted of best practice now dropped)
- National standard for post event reporting

f) R&D project W242 (Environment Agency, 2000c)

This project is the most comprehensive Agency study to date to investigate the performance of operational (and other) rainfall runoff models for a range of catchment sizes and types. The main recommendations for future research included:

- Techniques for assessing uniform response zones for catchments of different sizes and complexity guided by Digital Terrain Models and digital spatial datasets to help configure conceptual and other rainfall runoff models
- Investigations of raingauge weighting schemes across a range of catchments to develop some simple rules to determine which weighting schemes are appropriate for different catchments
- Assessment of forecast performance using Nimrod corrected radar rainfall actuals particularly for convective events
- Use of radar in flow forecasting during convective events including distributed grid-based models
- Further development of conceptual models for permeable catchments with groundwater abstractions, incorporating well data to support model calibration and updating
- New research into state updating schemes for models within the Agency which do not presently have them, and further development of schemes for existing models
- Improvement of methods for allowing for catchment wetness and variable baseflow in transfer function models together with automated real time updating techniques
- Development of a toolkit based approach where models can be built up from the most appropriate components to represent surface runoff, baseflows, hydrological units etc
- Evaluation of emerging technologies e.g. fuzzy logic, nearest neighbour, neural networks and re-evaluation of older techniques (e.g. ISO, IEM) which appear to work well for fast response catchments

g) NERC Town Meeting, London, 17 May 2001(no reference available)

This workshop on the Science of Quantitative Precipitation Forecasting also included a number of proposals for research into Real Time Modelling for flood forecasting applications both during the main session and in break out group sessions. These included:

- Development of probabilistic/ensemble flood forecasts with better integration of hydrological and meteorological models
- Development of distributed hydrological models using radar and DTM
- The need to develop first alert systems and ensemble based early warnings
- The need for inundation forecasting
- Forecasting for ungauged catchments
- The need for forecasting uncertainty and for decision support systems
- Forecasting for fast response catchments to three hours ahead for convective and large scale (embedded) convection

h) Two by Two workshop, Oxford, October 2001 (no reference available)

This joint Agency and Met Office workshop was held in October 2001 to discuss current progress and research needs in a number of areas including rainfall detection, real time forecasting, and dissemination of warnings. The Hydrometeorology Working Group outlined some of the priorities seen in the area of Real Time Modelling . Projects already funded included:

- Storm scale Numerical Weather Prediction project
- Uncertainty of Nimrod analysis project
- MORECS/MOSES-PDM comparison
- Early warning of extreme events (12 or more hours ahead)

with proposed projects including:

- Develop improved rainfall prediction methods including use of storm scale Numerical Weather Prediction models
- Assess the usefulness of emerging Numerical Weather Prediction capabilities in soil moisture and snow prediction
- Development of probabilistic approach to precipitation, runoff and river flow prediction as a basis for formal flood risk assessment and real time flood forecasting
- Assessment of the value of monthly/seasonal forecasts of flood and drought
- Diagnosis of uncertainty in Nimrod rainfall analyses and optimisation for real time modelling
- Finer resolution nowcast products (e.g. GANDOLF)
- Storm scale numerical modelling
- Optimising Nimrod for flood prediction (possible trial in NE Region)
- Real Time soil moisture estimation
- Snowfall and snowmelt estimation
- Long range rainfall prediction
- First guess early warnings of heavy rainfall up to several days ahead

i) *DEFRA R&D projects*

DEFRA sponsors research into flood and coastal defence to "help to inform policy development and to ensure that flood defence measures are delivered in a technically, environmentally and cost effective manner". The schedule of joint DEFRA/EA thematic R&D projects in flood and coastal defence (as of 14/2/02) includes the following new or proposed projects which have some relevance to flood warning:

- FD1913 Revitalisation of the FSR/FEH rainfall runoff method. Aims to improve the main components of the method, taking advantage of updated statistical methods, data and computational abilities (Oct 01-Sep 03)

- FD2012 Post event appraisal phase I. To provide the information and systems necessary for good post event performance evaluation (note: presumed to mean flood defences) (proposed)

- W5C(01)01 Development of flood warning management system. To develop a management system to record and present real time flood forecasting and warning information to facilitate decision making and to provide post event performance data (proposed Jan 02-Mar 04)

- W5C(01)02 Estimating antecedent conditions of catchment wetness. To evaluate and assess current methods of estimating catchment wetness that feed into rainfall runoff models (proposed Jan 02-Mar 03)

- FD2207 Storm scale numerical modelling. To start the development of the next generation convective forecasting capability (proposed Feb 02-Mar 05)

- FD2314 Concerted action on strategic approach to data and information. To identify data and information needs and sources for Coastal and Flood Defence and to develop R&D in monitoring, data management and development and application of new techniques (Feb 02-Feb 03)

- W5A(01)01 Reducing uncertainty in river flood conveyance. To develop improved tools and techniques for estimation of water levels for given flood discharge conditions, and to implement this management knowledge into flood forecasting, design etc (Jan 01-Jan 04)

- W5A(00))01 Hydraulic performance of bridges and other structures at high flows. To undertake a scoping study that will identify critical aspects of afflux and blockage… (Aug 01-Mar 03)

- FD2104/FD2105/FD2106 Continuous simulation. A number of projects aimed at improving techniques, rainfall data series etc for rainfall runoff modelling for both gauged and ungauged catchments using whole time series.

- FD2112 Advanced hydraulic modelling tool scoping study. To improve flood routing, hydrodynamic models and to produce a hydraulic routing model which is suitable for WCM, and provides acceptable computational speed (proposed June 02-Dec 02)

1.3 Summary of R&D Proposals

From the above description, it can be seen that over the past few years a number of topics have consistently appeared in assessments of Real Time Modelling R&D needs by flood forecasting practitioners.

Table 1.2. Recurring R&D themes on Real Time Modelling

Topic	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	This project
Post event evaluation and reporting techniques		Y		Y	Y				Y	Y
Tools for selection of optimum models		Y		Y		Y				
Improved real time updating techniques	Y	Y		Y		Y				Y
Probabilistic/ensemble forecasting with uncertainty		Y	Y	Y			Y	Y		RMF
Use of fully distributed rainfall runoff models	Y	Y	Y			Y	Y			
Integrating meteorological and hydrological models		Y	Y	Y	Y		Y	Y		RMF
Long lead time forecasts for flood storage uses			Y							
Improved rainfall detection (raingauge/radar)			Y							RMF
Decision support systems for extreme events	Y		Y	Y			Y			RMF
Clear targets for flood forecasting systems	Y		Y	Y						Y
Antecedent conditions in rainfall runoff models			Y	Y				Y	Y	Y
Toolkit based approach to model development				Y		Y				
Forecasting in ungauged catchments				Y			Y		Y	
Impacts of climate change				Y						
Model structures for extreme events				Y						
National data archiving strategy					Y					Y
Models for flooding from convective events					Y	Y	Y			RMF
Forecasting in fast response catchments					Y		Y			
Forecasting one-off events e.g. dam break					Y					
Models for groundwater flooding	Y				Y	Y				
Non linear transfer function models						Y				Y
Evaluation of new technologies						Y				Y
Monthly/seasonal forecasts for flood conditions								Y		
Snowcover and snowmelt modelling								Y		RMF

Some of these topics relate more to meteorological issues and are indicated by the code RMF to show that they are discussed in the Technical Report for the "Guidelines on Rainfall Measurements and Forecasting". In addition, the following forecasting problems were identified during the consultations with Agency staff earlier in this project:

- Fast Response Catchments
- Confluence Flooding
- Influence of Structures
- Floodplain Storage
- Low Benefit Locations
- Influence of Groundwater
- Urban Catchments
- Reservoired Catchments
- Complex Channels/Catchments

The highlighted entries in the table above are therefore suggested as additional candidates for potential R&D topics, based on a combination of need (i.e. forecasting problems), the results from the review and modelling studies in the present project, and the priority accorded in previous studies:

- Further development of fully distributed rainfall runoff models
- Improved models for groundwater dominated flooding
- Decision support tools for real time model selection
- Decision support tools for fast response catchments

The tools for model selection project is envisaged as the logical next step from the present project, providing Agency staff with operational software tools incorporating digital terrain models, GIS, meteorological and hydrological databases etc to assist in the model selection process. The remaining projects envisage the further development and evaluation of models aimed at solving current forecasting problems; for example, early recognition of the conditions leading to extreme, fast response flooding (to supplement rainfall runoff modelling) and estimates of the likely impacts, or models to support the difficult decision making made – for example – in the Chichester area in Autumn 2000 where there was a combination of groundwater and surface runoff flooding.

The final list of proposed projects is shown in outline Form A's in Appendix A.3

2. CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed the current situation regarding the use of Real Time Models in flood forecasting in the UK and elsewhere. This has included an assessment of the advantages and limitations of each approach leading to the following general conclusions concerning recommended future R&D and other requirements.

a) R&D/operational. Framework for evaluation of the performance of real time models. This project has identified post event analysis/data archiving as a key issue and has recommended techniques which might be adopted nationally. This will require procedures to be devised for routine post event analysis, archiving of the results (raw data and interpreted values), interpretation of the results, and dissemination of this information to interested parties. Additional R&D has also been recommended to develop procedures and tools to assist operational staff, model developers and researchers in performing post event analyses of the performance of the types of individual real time models (rainfall runoff, routing etc) which comprise a real time flood forecasting system.

b) R&D/operational. Review of high level targets for flood forecasting. To review and possibly rationalise the Agency's targets for flood warning to meet the needs of real time modellers and, if changed, to produce best practice guidelines for practitioners how these revised targets relate to the design of the modelling component of systems, and those which relate to performance of the whole flood warning system

c) R&D/operational. Guidelines, training, decision support. The guidelines identify best practice in use of Real Time Modelling, and this technical report discusses the current situation in the UK and internationally. It will be an ongoing Agency task to update the guidelines to take account of new developments and possibly to monitor the take up of best practice recommendations. There is also a potential R&D need to develop a prototype intranet based decision support tool to assist flood forecasting practitioners in the application of the real time model selection guidelines developed under this project.

d) R&D. Transfer function modelling. To research alternative model structures and ways of using real time data in order to develop best practice guidelines to assist flood forecasting practitioners in the selection, calibration and operation of transfer function models for real time flood forecasting

e) R&D. New approaches to rainfall runoff modelling. To review new and emerging techniques for rainfall runoff modelling in the UK and internationally and to evaluate their performance on a number of representative test catchments.

f) R&D. Real time operation and updating of hydrodynamic models. To develop best practice guidelines for the conversion of simulation models to real time use with particular emphasis on updating techniques and stability in real time operation

g) R&D. Next generation distributed models. To review the latest distributed rainfall runoff modelling techniques and to evaluate selected models on catchments in England and Wales in an operational situation using the latest Nimrod and MOSES products

h) R&D. Improved models for groundwater dominated flooding. To develop improved procedures for forecasting groundwater dominated flood events and guidelines for use by flood forecasting practitioners.

i) R&D. Rainfall runoff models for ungauged/low benefit locations. To develop and evaluate improved techniques for flood forecasting at ungauged and low benefit locations with the aim of providing a more targeted/technically sound flood warning service at such locations.

j) R&D. Decision support tools for fast response catchments. To review international computer-based approaches to real time flash flood forecasting and to evaluate and demonstrate their application under UK conditions for several representative high risk (e.g. urban) catchments.

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APPENDIX A

General Flood Forecasting Glossary and List of Abbreviations/Acronyms

Source: National Flood Warning Centre (Latest versions obtainable from the same location)

GLOSSARY

TERM	DEFINITION / DESCRIPTION
1-D *hydrodynamic* modelling:	A *modelling approach* based on the Saint-Venant equations capable of predicting discharge and water level for a wide range of rivers, reservoirs, complex floodplains and narrow estuaries.
2-D *hydrodynamic* modelling:	A *modelling approach* based on the *shallow water wave* equations capable of predicting flows and water surface elevations in two dimensions. The approach can cope with lateral variations in depth and velocity and is particularly useful in modelling wide estuaries and flows over side-weirs.
Attenuation:	A characteristic flattening of discharge hydrographs, reduction in the magnitude of peak flows and an increase in flood duration associatd with temporary storage along a river reach, reservoir or across a floodplain.
Automatic calibration:	The calibration of a mathematical model using optimisation methods by minimising some measure of error criterion called objective function.
Average Annual Damage (AAD):	Damage likely to occur over a one-year period expressed as an average value per year.
Base Model	A calibrated and verified model.
Baseline:	The present condition of the river or estuary.
Benefits:	Economic, environmental etc gain in terms of (flood defence – the damages avoided).
Calibration:	The process of back-calculating or estimating the values of empirical parameters inherent in the governing equations. The process is often carried out through trial-and-error comparisons of gauged and simulated values.
Code or Computer Program	A series of *algorithms* often capable of processing input data to produce output data.
Compensation flow	Water released from a reservoir or a diversion structure to meet the needs of downstream (‘riparian’) water users and/or to satisfy environmental requirements.
Conceptual Hydrological Models	A *modelling approach* transforming rainfall to runoff by allowing for a whole range of catchment storage reservoirs through notional storage volumes.
Continuous modelling	A flood forecasting practice based on continuously running flood-forecasting models.
Dataset	A collection of data that represents the physical characteristics or some other abstract description of a particular catchment or a river system.
Deterministic Models	Models that attempt replicate physical processes by explicitly modelling the laws of nature governing the process.
Empirical modelling:	A *modelling approach* often developed by fitting a mathematical function to observed data using regression analysis or some other mathematical methods. The classical example is the Manning equation for normal flows. In forecasting, threshold exceedence and level-to-level correlation techniques are also other examples.
Flood Forecasting	The prediction of peak flows and levels and the times that they will occur.
Flood Routing:	Routing is a term given to calculation procedures for determining the modification of waveforms as flood waves travel in open-channels. Broadly, there are two methods (**i**) *hydrological routing* (encompassing *channel routing* and reservoir routing), (**ii**) *hydraulic routing* (encompasses *kinematic routing*, diffusion analogy, and *hydrodynamic routing*.
Forecasting Platform	The hardware system used to host forecasting software.
Graphical User Interface (GUI)	A piece of software that can display raw or processed data and allow a user to control the performance and operation of software packages and modelling applications.
Hazard:	The potential for adverse outcomes. In the case of flooding, the hazard relates to the inundation of land by floodwater posing threats to life, inflicting damage and/or disruptions.
Household Equivalent (HE):	Unit of measurement for property susceptible to flooding.

Holistic Catchment Management:	A management philosophy allowing for interactions among a whole range of factors affecting catchment behaviours.
Hydrograph:	A time history or time-series of a certain hydraulic variable such as discharge or water level.
Hydrological Routing	A *modelling approach* for routing discharge hydrographs by a water budget equation (inflow-outflow = rate of change of storage). "Channel routing" or the Muskingum method refers to cases in which storage is a function of inflows and ouflows and "storage routing" to cases in which storage is a function of outflows.
Hyetograph	Time distribution of rainfall, which is also referred to as "rain profile." Hyetographs are normally bar chart displays of measured/forecasted depths of collected rainfall in regular intervals (say 15 minutes).
Intake:	Structure through which water is drawn out of a river.
Inter-tidal:	Between the levels of low tide and high tide.
Lead time:	The time by which the forecast of an incident precedes its occurrence (or non-occurrence).
Low water:	Lowest water level reached by each ebb tide.
Model (or Mathematical Model)	A program that processes data in its own specific format and then performs internal calculations to derive predicted flows or water levels.
Model Verification	A confidence building process in modelling, whereby the calibrated model is further used to independently predict an independently gauged event meeting the same criteria as used in calibration.
Modelling Packages or Proprietary Packages	It is now customary to develop user-friendly codes through front-end model development and back-end result processing facilities, in which case the codes are referred to as software. Modelling Packages are normally proprietary packages e.g. HEC-RAS, ISIS, Mike11.
Modelling Procedure	The life cycle of a modelling project. This includes inception, schematisation, data abstraction, building a preliminary model, calibration, verification and its eventual applications.
Modelling Shell	A proposed term to refer to *modelling/forecasting system* where a wide range of *software packages* and other software utilities and *modelling applications* are accessible for users. Software utilities include *Graphical User Interfaces* (GUI). Modelling shell does not normally refer to datafiles or result-files.
Modelling System	A proposed term to encompass *Modelling shell*, *software packages*, software utilities, *base model* and *modelling applications*. This may equally be referred to as modelling/forecasting system.
Monitoring:	Regular interrogation of hydrometric data (especially river levels) with a view to intensifying such activity, initiating forecasting, or issuing warnings if pre-set levels exceeded.
Neap tides:	Tides on the tow occasions per lunar month when the predicted range between successive high water and low water is least.
Opportunity Benefits:	Economic benefit available through achieving improved target standards of service.
Open Architecture:	A system that admits third party software packages or off-the-shelf products without the intervention of the system producers. This is only possible if the architecture of the system is modular and the various modules have published interfaces.
Post Event Appraisal:	Studies undertaken after a flood incidence for assessing the effectiveness of incidence management.
Post-audit:	Review of flood forecast or flood warning performance following a flood incidence or a flood season to quantify the performance of the forecast and warning system.
Rainfall-runoff models:	Models that transform rainfall to runoff. Rainfall-runoff models may be metric ('black-box'), conceptual, physically based or hybrid metric-conceptual: and may use an lumped input of catchment average rainfall, or a distributed input.
Reach:	A length of channel between defined boundaries.
Risk assessment:	A decision making approach often encompassing a formalised procedure.
Risk:	A risk is the likelihood of an adverse event. **Risk = likelihood x hazard**. Thus, risk is the combined effect of the probability of occurrence and hazard.

Sea level rise	Increase in mean sea level due to global warming and climate changes.
Sea State Forecasting	Prediction of offshore and near shore conditions based upon wave, wind, tide, weather, pressure and surge conditions
Sediment transport:	Movement of sediment under the action of waves and currents
Sensitivity analysis:	Assessment of the impacts of system parameters or other factors such as boundary conditions on model results by systematically varying their values.
Shallow water waves	Water waves in open channels driven by gravity with an appreciable displacement of bulk water in a direction parallel to the flow. Flood waves are *shallow water waves*.
Shell	A software system that receives and stores raw external data together with Model Datasets and model results. It controls the operation and performance of the hydraulic and hydrological or other Models that are included within it through an associated Graphical User Interface
Stochastic models:	Processes in which the processes are governed by extremely large number of causative factors that are therefore considered to be randomly governed.
Updating	Updating is the process of utilising measurements of water levels or discharges in the pre-forecast period to correct for minor deviations in simulated values during the forecast period.

ABBREVIATIONS and ACRONYMS

Abbreviation	Definition
1-D	One Dimensional
2-D	Two Dimensional
AFFMS	Anglian Flow Forecasting Modelling System
Agency	Environment Agency
AMAZON	An overtopping software application
ANN	Artificial Neural Network
ARCView	A proprietary GIS product
ARSP	Acres Reservoir Simulation Package
ARTS	Anglian Region Telemetry System
AVM:	Automatic Voice Messaging
CASCADE:	Catchment Assessment System Concerned with the Accurate Dissemination of Effective flood warnings.
CCTV	Closed Circuit Television
CEH:	Centre of Ecology and Hydrology (formerly IH : Institute of Hydrology)
CIS	(The Agency's) Corporate Information Services (department)
CNFDR:	Changing Needs in Flood Defence Review
CoBA	Cost Benefit Assessment
CRC	Cyclic Redundancy Check
CSCE	Canadian Society for Civil Engineering
CSM	Continental Shelf Model
DEFRA	Department of Environment, Food and the Environment
DELFT-FEWS	Delft Hydraulics' Flood Early Warning System.
DEM	Digital Elevation Model
DETR	Department of Environment, Transport and the Regions
DHI	Danish Hydraulics Institute
DL	Dynamic Logic – a Telemetry System & Outstation Supplier
DODO	Douglas and Dobson Routing Model
DOS	Disk Operating System
DSS	Decision Support System
DSSY	Data Storage System
DTM	Digital Terrain Model
DTS	Delta Technical Services
DWOPER	A Hydrodynamic Model produced by the United States National Weather Service
EFA:	Easter Floods Actions
EFAG:	Easter Floods Action Groups
EFAP:	Easter Floods Action Plan
EFFORTS	European Flood Forecasting Operational Real-Time Systems project
EFFS	European Flood Forecasting System (see EFFORTS)
ELFS	Emergency Level Forecasting System
EMS	Energy Management System
ERLOS:	Emergency Response Levels of Service
EURAQUA	EU initiative / project
EUROTAS	European River Flood Occurrence and Total Risk Assessment System
FEFLOW	Finite Element Flow software application
FFMS	Flood Forecasting Modelling System
FFP	Flood Forecasting Platform
FFS	Flow Forecasting System – part of the Midlands Region system
FFWRS:	Flood Forecasting and Response Warning System.
FHRC	Flood Hazard Research Centre at Middlesex University
FRA	Flood Risk Area
FRONTIERS:	Forecasting Rain Optimised Using New Techniques of Interactively Enhanced Radar and Satellite Data. An interactive radar rainfall based system system developed by the

	Met Office for forecasting rainfall for up to six hours ahead. Predecessor of NIMROD.
FTP	File Transfer Protocol
GANDOLF	Generating Advanced Nowcasts for Deployment in Operational Land-based Flood Forecasts. A system developed by the Met Office for forecasting convective rainfall.
GEO BASE	Geological Database
GEOHEC -1	Watershed Modelling System (old version)
GIS	Geographical Information System
GMS	Groundwater Modelling System
GUI	Graphical User Interface
HARP	Hydrometric Archive Replacement Program. Currently the Environment Agency are seeking to procure a National System for archiving hydrometric data.
HE	Household Equivalent
HEC	Hydrologic Engineering Centre (an Office of the US Army Corps of Engineers).
HEC-RAS	Open channel River Analysis System using steady state solver
HEC-RAS3	The latest version of the above, uses hydrodynamic solver
HR Wallingford	Hydraulics Research Wallingford
HYDRO-1D	A Hydrological and Hydrodynamic Modelling System developed and marketed by Mott McDonald Ltd
HYRAD	Weather Radar Display software developed by CEH
IAHR	International Association Hydraulic Engineering & Research
ICA	Information Control Algorithm, a component of RFFS
IHACRES	Rainfall-Runoff model developed by IH an d the Australian Centre for Research into Environmental Systems.
IH	(The) Institute of Hydrology, now know as CEH
IPC	Integrated Pollution Control
ISIS	Hydrological and hydrodynamic Modelling System developed and marketed by the joint venture between Wallingford Software and Sir William Halcrow and Partners Ltd.
IT	Information Technology
JCH-MR	Joint Centre for Hydrological & Meteorological Research. A joint Met Office / CeH centre located at CeH Wallingford.
JTP	Joint Telemetry Project
KW	Kinematic Wave model – part of RFFS
LAN	Local Area Network
LIDAR	Laser Induced Direction And Ranging
MAFF	Ministry of Agriculture Fisheries and Food (superseded by DEFRA)
MATRICES	A Sea State software application
MCC	Meteor Communication Centre
MCL	Meter Communications (Europe) Ltd
MDS	Model Development System – see OMDF
Met Office	UK National Meteorological Office
MFFS	Midland Flow Forecasting System – term used for the new system for the Midlands Region to replace the current FFS
Mike 11	The Hydrological and Hydrodynamic Modelling System developed and marketed by the Danish Hydraulic Institute
Mike ACS	The Mike11 module for Multi-layer Cohesive Sediment
MIKE BASIN	River Basin Modelling
Mike DB	The Mike11 module for Dam Bursts
Mike HD	The Mike11 hydrodynamic module
Mike NAM	The Mike11 module for Rainfall Runoff
MIKE SHE	Distributed Hydrological Modelling
Mike SO	The Mike11 module for Structure Operations
MIKE SWMM	Stormwater and Wastewater Modelling Package
Mike UD	The Mike11 module for Urban Drainage
Mike WQ	The Mike11 module for Water Quality
MIKE ZERO	Common Platform for DHI Products
MIST	Meteorological Information Self-briefing Terminal – a Met Office display system for

	viewing a range of their products.
MORECS	Met Office Rainfall and Evaporation System - Soil Moisture Information Service operated by the Met Office
NAM	The Mike11 module for Rainfall Runoff (now renamed to MKE11-RR)
NERC	Natural Environmental Research Council
NFFMS	National Flood Forecasting Modelling Systems
NFWC	National Flood Warning Centre
NFWPS:	National Flood Warning Performance Specification
Nimrod	A fully automated system developed by the Met Office for forecasting (non-convective) rainfall for lead-times of up to six hours.
NMC	National Meteorological Centre at Bracknell
NTS	National Telemetry Specification
NWRS	National Weather Radar Strategy
NWSRFS	Stream Flow Forecasting System
ODIN	Outstation Data Interrogation System
OMDF	Off-line Model Development Facility
PBT	Parsons Brinckerhoff Ltd (in UK formerly Kennedy & Donkin)
PDM	Probability Distributed Moisture model - a rainfall-runoff model developed by CeH.
PHR:	Proportion of households able to respond to a warning.
POL	Proudman Oceanographic Laboratory, part of NERC
PRRS	Particular Regional Requirements Specification
PRTF	Physically Realisable Transfer Function model (developed at the University of Bristol)
PSTN	Public Switched Telephone Network
R&D	Research and Development
RADAR	Radio Detection and Ranging
RADARNET	Met Office Radar Communications Network
RCC	Regional Communications Centre
RECS	Regional Emergency Communications System
RECS/FFS	The telemetry and flood forecasting system currently used in Midlands region
REMUS	Remote User System (for FFS)
RFFS	River Flow Forecasting System
RMS	River Modelling System
ROFFMS	Real-Time Operational Flood Forecast Modelling System
RTI	Riverside Technology Inc
RTS	Regional Telemetry System
SAAR	Standard Average Annual Rainfall
SCS	Soil Conservation Service
SCX	Telemetry Kernel Software for Serck Controls systems
SEEP2D	Ground Modelling System (old version)
SEFFS	Southern (Region) Enhanced Flood Forecasting System
SEPA	Scottish Environmental Protection Agency
SMS	Surface Water Modelling System
SSADM	Structure Systems Analysis and Design Method
STFS	Storm Tide Forecasting Service
STOAT	WRC – Software application for STW Modelling
STORM SHED	Hydrology Modelling software application
TAG	Theme Advisory Group (to the joint Agency/MAFF R&D Programme)
TF	Transfer Function
TFF	Tidal Flood Forecasting
TFFP	Tidal Flood Forecasting Project
TideBase	A system for displaying tidal data used by the Agency.
TIDEBASE	A standalone system for displaying Met Office tidal data
TIDELINK	A system for displaying Met Office tidal data developed at the Thames Barrier
TIDEPOL	Software operated by the Met Office to poll the “A” class tidal gauge network with the ability to forward data to the Thames Barrier.
TREND2	Trend Standard Report Packaging
URS	User Requirement Specification

USACE	United States Army Corp of Engineers
USCS	Unified Soil Classification System
USGS	United States Geological Survey
WAN	Wide Area Network
WINDATA	Rain Rate Forecast Package
WMS	Watershed Modelling System
WRIP	A rainfall-runoff modelling system developed by the University of Bristol

APPENDIX B

Regional Forecasting Issues

(Source: EA Regions – in response to questionnaire)

LIST OF POTENTIAL CASE STUDY EXAMPLES FOR ASSESMENT OF COMMON FORECASTING PROBLEMS

NOTES to Respondents

Typical forecasting problems might include:	Flashy Upland Catchments Urban Catchments Forecasting Flood Levels at Confluence Forecasting Influence of Structures Forecasting Groundwater Flooding Forcasting for Low Benefit Locations *Upto three examples of each problem is sufficient*
Specific description of problem might be:	Forecasting for specified flood risk zones in upstream part of catchment Forecasting for specified flood risk zone upstream/downstream of a structure *Forecasting problems due to poor data availability not required*
Survey types might include:	In-bank topographic channel survey Full floodplain topographic survey LiDAR survey

EA REGION: MIDLANDS **PREPARED BY:** TIM HARRISON

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem		Data Availability for River/Reaches Specified			
			Model (specify)	Gauging (1-good to 3-poor)			Survey (specify)
				Flow	Level	Rainfall	
Forecasting flood levels at confluences	Severn/Teme	Floodplain storage & backing up.	Routing	3	1	1	?
	Severn/Vyrnwy	Floodplain storage & backing up.	Routing	3	1	1	?
	Sow/Penk	Floodplain storage & backing up.	Rainf/RO & Routing	3	1	1	?
	Middle Trent	Floodplain storage & backing up.	Routing	3	1	1	?
Flashy upland catchments	Wye		Rainf/RO	2	1	1	?
Forecasting influence of structures	Soar	Pillings Lock gauge & various radial gates.	Rain/RO & routing	1	1	1	?
Urban catchments	Upper Tame	Timing of forecast peak is poor, but critical.	Rain/RO & routing	2	1	1	?
Forecasting for low benefit locations	Leam	Perceived low benefit as thought there were only 9 properties which flooded- proved wrong at Easter 98!	Rain/RO & routing	3	2	1	?

Contact Shirely Greenwood at
Sapphire East for survey data

EA REGION: NORTH WEST **PREPARED BY:** IAN PEARSE

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem		Data Availability for River/Reaches Specified			
				Gauging (1-good to 3-poor)			
			Model (specify)	Flow	Level	Rainfall	Survey (specify)*
Influence of Structures	Wyre to St Michaels	Upstream flood basins and hydrograph changes.	Correlation	1	1	1	
Confluence	Derwent at Cockermouth	One tributary affected by lake.	Summation of flows	2	1	2	
No Model	Yarrow at Croston	No Model.	RFRO	2	1	1	
Flashy Pumped Catchment	Glaze	Bedford and Lilford pumped catchment.	None	1	1	1	
Multiple Upstream Reservoirs	Etherow at Woolley Bridge	Multiple Upstream Reservoirs.	Spreadsheet	2	2	2	

* Survey information to be forwarded/available from Peter Spencer at RFH.

EA REGION: WALES (NORTH) **PREPARED BY:** S.MAYALL

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem		Data Availability for River/Reaches Specified			
				Gauging (1-good to 3-poor)			
			Model (specify)	Flow	Level	Rainfall	Survey (specify)
Llanrwst	Conwy	Flashy Upland Catchments.	Rainfall/Runoff	2	1	3	
		Forcasting for Low Benefit Locations.					
		Forecasting problems due to poor rainfall forecast data availability.					
Machynlleth	Dyfi	Flashy Upland Catchments.	Rainfall/Runoff	2	1	3	
		Forecasting Influence of Structures.					
		Forecasting problems due to poor rainfall forecast data availability.					
Dolgellau	Mawddach/Wnion	Flashy Upland Catchments.	Rainfall/Runoff	2	1	3	
		Forecasting Influence of Structures.					
		Forecasting problems due to poor rainfall forecast data availability.					
Lower Dee Floodplain	Dee	Impact of tidal effect.		1	1	2	
		Floodplain storage.					
		Forecasting Flood Levels at Confluence(s).					
Lower Glaslyn Floodplain	Glaslyn	Impact of tidal effect.		3	2	2	
		Floodplain storage.					
		Forecasting Flood Levels at Confluence(s).					

EA REGION: NORTH EAST **PREPARED BY:** DOUG WHITFIELD

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem		Data Availability for River/Reaches Specified			
				Gauging (1-good to 3-poor)			
			Model (specify)	Flow	Level	Rainfall	Survey (specify)
Flashy Urban upland Catchments	Walsden Water	Walsden (tributary of upper Calder)	PDM	3	1	2	In-bank topographic channel survey
	Upper Calder	Todmorden, Hebden Br and Mytholmroyd.	PDM + KW	3	2	2	In-bank topographic channel survey
	River Sheaf, Sheffield	Gauge at bottom of catchment, floods also influenced by debris screen at culvert entrance.	PDM	2	2	1	In-bank topographic channel survey
Levels at Confluences	Boroughbridge	Levels in Boroughbridge affected by River Ure confluence with Swale some distance downstream.	PDM + KW in addition to Muskingham based alternative.. Non real-time HD model also available	2?	1	1	Full floodplain topographic survey
	Castleford	Confluence immediately upstream + town bypassed by flood storage/bypass channel.	PDM +KW as well as other techniques	2?	1	1	Full floodplain topographic survey
Forecasting Influence of Structures	River Don basin (Dearne and Rother especially)	5 river regulators used to reduce peak flows in Doncaster. Control rules very loose. Difficult to apply what if modelling in RFFS with so many variables.	PDM + KW	2/3	1	1	Lidar + cross-sections
	River Tees	Tees Barrage affects levels in lower reaches.	PDM + KW + real time ISIS	1?	1	1	Various
Forecasting Groundwater Flooding	River Hull catchment	Fed by Yorkshire Wolds aquifer. Also under tidal influence with difficult gauging.	Non real-time HD	2?	1	1	Various
Uncontrolled Floodplain Storage	Many - good example Lower Tees	KW models do not represent floodplain storage. Resolved by implementation of real-time ISIS.	PDM + KW + real time ISIS	1?	1	1	Various

EA REGION: SOUTHERN **PREPARED BY:** MIKE VAUGHAN

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem		Data Availability for River/Reaches Specified			
			Model (specify)	Gauging (1-good to 3-poor)			Survey (specify)
				Flow	Level	Rainfall	
1= Flooding from groundwater dominated rivers	Lavant	Chichester	ISO Function	2	2	2	???
	Ems	Area 3A1	Linear TF	2	2	2	???
	Itchen	Winchester	N/A	3	2	2	???
1= Small catchments where rainfall forecasts required for adequate forecast leadtime	Cuckmere	Hellingly	Non-linear transfer function	3	2	2	???
	Tadburn Lake (Not a lake, but a stream)	Romsey	Linear TF	2	2	2	???
	Hamstreet Arm, Speeringbrook Sewer	Hamstreet	N/A	3	2	3	???
3 Forecasting flood levels at confluences	Medway	Yalding	None	3	2	2	???
4 River and tide combined	Ouse	Lewis	N/A	3	2	1	???
	Great Stour	Canterbury	N/A	2	2	2	???
	Medway	Maidstone	N/A	1	2	2	???
5 Groundwater flooding (away from watercourses)	Test	NW part of catchment	N/A	N/A	2	2	???
	Brighton Chalk Block	Patchams	N/A	N/A	2	2	???
	Nailbourne	Many places	N/A	N/A	2	3	???

EA REGION: THAMES **PREPARED BY:** N.OUTHWAITE

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem		Data Availability for River/Reaches Specified			
			Model (specify)	Gauging (1-good to 3-poor)			Survey (specify)
				Flow	Level	Rainfall	
Rapid response of urban catchments, particularly coupled with convective rainfall events	River Ravensbourne	Time-to-peak at Kyd Brook Close is approx. 1 hour, although can be as little as 15 mins. Sudden development of ‘clear air’ convective events means that achieving 2hr lead time is a problem.	ISIS Model	3	1	2	Full floodplain topographic survey
Complex channel networks, with small (<0.1m) differences in level resulting in considerable variations in property flooding	River Thames at Oxford	River Thames splits into a no. of different channels as it passes through Oxford. Some structures to influence flow splits. Small increases in level ie. 0.1m can mean no properties flooding or 90 properties flooding – 0 properties in November 2000, 92 in December .	ISIS/ONDA	2	2	1	Full floodplain topographic survey
	Lower River Colne	River Colne splits into a large number of channels in lower reaches, each of which has its own flooding problems. Difficult to forecast flows/levels in each individual channel.	ISIS/ONDA	1	1	1	In-bank topographic channel survey
Flooding at confluences	River Loddon	Properties at risk of flooding from either Thames or Loddon or combination of both. Uncertainty of flooding processes makes it difficult to forecast need for warnings.	ISIS model of Thames, nothing for Loddon	1	1	2	Full floodplain topographic survey
Groundwater flooding	River Lambourn	High groundwater levels result in prolonged periods of high river levels at Lambourn.	No models	3	2	2	No survey data
	River Misbourne	High groundwater levels result in prolonged periods of high river levels at Missenden.	No models	2	2	2	No survey data

EA REGION: SOUTH WEST **PREPARED BY:**

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem		Data Availability for River/Reaches Specified			
				Gauging (1-good to 3-poor)			
			Model (specify)	Flow	Level	Rainfall	Survey (specify)
Overtopping of Flood Defences	River Tone, Somerset	4-6 hours lead time required to issue a reliable flood warning to trigger a Major Incident Plan (MIP) for Taunton.	Rainfall runoff using total rainfall (WRIP)	1	2	1	Check with Robin Bendell, Bridgwater Office
Flashy Upland Catchments	River Sid, Devon	Insufficient time to issue a 2-hour flood warning.	Level criteria	3	2	2	Check with Andrew Latham, Exminster Office
Flashy Upland Catchments (2nd choice)	River Wey, Dorset	Insufficient time to issue a 2-hour flood warning.	Level criteria	1	2	1	Check with Duncan Riches, Blandford Office
Forecasting Groundwater Flooding	River Avon, Hampshire	Salisbury flood defences nearly overtopped. No rainfall runoff model to predict impact of rain on river flows.	Level criteria	1	3	1	Check with Duncan Riches, Blandford Office
Tidal/fluvial interaction	River Taw, Devon	Barnstaple – difficult to quantify the interaction between river flood and tidal level.	Level criteria, wind surge and forecast	1	3	2	Check with Andrew Latham, Exminster Office
Mixed storage catchments	River Stour, Dorset	Hammoon flow station, rapid response which levels off and is sustained for several days.	Rainfall runoff using total rainfall (WRIP)	1	2	1	Check with Duncan Riches, Blandford Office

EA REGION: WALES – SW AREA **PREPARED BY:** JR FROST

Top Five Forecasting Problems (listed in order of priority)	River Exhibiting Problem	Specific Description of Problem	Model (specify)	Data Availability for River/Reaches Specified			
				Gauging (1-good to 3-poor)			Survey (specify)
				Flow	Level	Rainfall	
Flashy Upland Catchment	Ogmore	Fast rising river with time to peak of less than 3 hours – needs good rainfall forecast.	Trigger levels used at present	1	1	2	
	Tawe	Fast rising river with time to peak of less than 3 hours – needs good rainfall forecast.	Trigger levels used at present	2	1	2	
	Afan	Fast rising river with time to peak of less than 3 hours – needs good rainfall forecast.	Trigger levels used at present	2	1	2	
Low Benefit Locations	Teifi	800km^2 with isolated properties affected. Poor correlation relationships between 3 level gauges because of variability of rainfall in time and space, and shape of catchment, and raised peat bog in upper catchment.	In-house hybrid rational rainfall runoff model.	2	1	1	
	Solva	Problem is forecasting when upstream on-stream flood alleviation scheme will fill.	In-house hybrid rational rainfall runoff model.	2	1	1	
Floodplain Storage	Cynin/Dewi Fawr	River rises steeply and then flattens out as river overtops into floodplain upstream of flood risk area. This makes updating of forecast with measured levels very difficult in real time.	In-house hybrid rational rainfall runoff model.	2	1	1	
	Taf	River rises steeply and then flattens out as river overtops into floodplain upstream of flood risk area. This makes updating of forecast with measured levels very difficult in real time.	In-house hybrid rational rainfall runoff model.	1	1	1	
Hydropower Generation	Rheidol	70% of catchment upstream of flood risk area is part of hydropower scheme. We have threshold for onset of flooding but reservoir storage and power operation procedures make forecasting of peak and time difficult. Largest reservoir has not filled in last 30+ years but it might one day.	In-house hybrid rational rainfall runoff model.	2	2	1	

APPENDIX C

DEFRA / EA Short Form A for R&D Outline Project Proposals for 2003/04

TITLE: *REAL TIME OPERATION AND UPDATING OF HYDRODYNAMIC MODELS*

Purpose (Key Customer) - Why is the R&D needed?
Hydrodynamic models are increasingly being used within the Agency for modelling river reaches in which complex effects (tidal, structures etc) make use of simpler routing models unsatisfactory. Research and best practice guidelines are required into best practice use of these models in real time, particularly when converted from Section 105 models, and including evaluation of techniques for real time updating and regular recalibration

Summary (Overall) Objectives
To develop best practice guidelines for the conversion of simulation models to real time use with particular emphasis on updating techniques and stability in real time operation. To examine the resource implications for the Agency of using and maintaining such models and compare this with the benefits of improved flood forecasts

Context (Background)
Hydrodynamic models are increasingly being used within the Agency for modelling river reaches in which complex effects (tidal, structures etc) make use of simpler routing models unsatisfactory. The many Section 105 models that have been calibrated since the Easter 1998 floods also have potential for conversion to real time use. Although the process of converting a simulation model is straightforward, approximations are sometimes required (e.g. a reduced spatial extent) and failures due to initialisation errors, problems at low flows etc are not acceptable in an operational system. In particular, the issue of real time updating, considered essential for many other types of real time model, is more difficult to implement for hydrodynamic models, since mass must always be conserved and disturbances arising from flow adjustments may propagate through the system. Evaluation of appropriate updating techniques for hydrodynamic models is required (e.g. state updating via tributary inflows, or parameter updating via roughness coefficients), and general guidelines on best practice in converting simulation models (e.g. Section 105 models) to real time use, with particular emphasis on calibration for high flows/uncertain ratings. The review should also consider possible new applications for real time use; for example, real time inundation mapping, and techniques for simulating event-specific problems (e.g. blockages by debris, breaches of flood defences, partial or complete failures at river flow control structures etc) and making use of related instrumentation (e.g. differential level sensors, CCTV). Interfacing this work with the Agency's overall Forecast Model Systems Strategy will be essential.

Main Outputs / User / Benefits
Research report and best practice guidelines
Flood forecasting and warning staff
Improved practice in use of hydrodynamic models for flood forecasting

Timescale / Costs / Costs by year: 15 months £120k

Other Funders (internal or external)?
One of the modelling houses may be interested in contributing (HR, DHI, Delft)

PREPARED BY: Andrew Grime
e-mail address: andrewgrime@weetwoodservices.demon.co.uk

Which one of the following types of R&D would this project come under:

Operational	Policy	Strategy

Which would be the main EA Theme that this project would come under:

Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife

Principal DEFRA / EA Theme: Flood Forecasting & Warning

TITLE: *IMPROVED MODELS FOR GROUNDWATER DOMINATED FLOODING*

Purpose (Key Customer) - Why is the R&D needed?

Groundwater dominated flooding has been a major issue in recent flood events particularly in Southern and Anglian Regions. The current modelling techniques could possibly be developed through improved monitoring and modelling of groundwater conditions and flows and of the interaction between groundwater and surface water flows

Summary (Overall) Objectives

To develop improved procedures for forecasting groundwater dominated flood events and guidelines for use by flood forecasting practitioners.

Context (Background)

Groundwater-related flooding has been a serious problem in recent flood events; for example, spring flows being much higher than usual (or appearing in new locations), and increased river runoff due to saturated soil conditions. The risk is particularly high in urban areas. At present, a range of correlation and simple rainfall runoff modelling procedures are used to forecast this type of event, but there remains the potential for improvement; for example, use of real time monitoring of well levels (e.g. by piezometers) and soil moisture, and development of improved groundwater flow components in semi distributed and distributed conceptual rainfall models (with allowance for pumped abstractions/recharge etc). Existing three dimensional numerical aquifer models, developed for water resource applications, could possibly also be adapted for quasi real time use e.g. daily runs. Research is required into both improved monitoring techniques and models. However, there are several concerns with potentially using detailed groundwater modelling as a prediction tool. The high number of variables and the apparent lack of groundwater data to correlate it to represent a problem. This is compounded by the high variability of hydrogeological conditions along individual river reaches. It is probable that any modelling approach would be limited in the extent over which it could be applied. The development of a predictive tool for forecasting should concentrate on correlation analysis. Initial findings may show that without significant increases in monitoring it is not possible to apply catchment wide groundwater models at the sub-catchment level

Main Outputs / User / Benefits

Site characterisation and correlation analysis followed by a review stage to develop the best way forward and identify improved techniques for forecasting groundwater dominated flooding (based on simplified catchment models?)

Flood forecasting and warning staff

Improved methods for forecasting groundwater dominated flooding

Timescale / Costs / Costs by year: 8 months £60k

Other Funders (internal or external)?

PREPARED BY: Andrew Grime
e-mail address: andrewgrime@weetwoodservices.demon.co.uk

Which one of the following types of R&D would this project come under:

Operational	Policy	Strategy

Which would be the main EA Theme that this project would come under:

Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife

Principal DEFRA / EA Theme: Flood Forecasting & Warning

TITLE: *NEXT GENERATION DISTRIBUTED RAINFALL RUNOFF MODELS*

Purpose (Key Customer) - Why is the R&D needed?
Recent developments in weather radar signal processing and forecasting systems (Cyclops, Nimrod, MOSES) mean that rainfall, snow cover and soil moisture data are available at a much higher spatial and temporal resolution than in the past. A review and comparative study of grid based distributed models is therefore timely, with possible advantages in flood forecasting for complex (e.g. urban) catchments and during thunderstorms.

Summary (Overall) Objectives
To review the latest distributed rainfall runoff modelling techniques and to evaluate selected models on catchments in England and Wales in an operational situation using the latest Nimrod and MOSES products.

Context (Background)
Most rainfall runoff models used within the Agency's flood forecasting systems are presently of the lumped or semi-distributed type, in which spatial variations in rainfall across a catchment (or subcatchment) are neglected. Grid based distributed models, combined with GIS/DTM datasets, offer the potential to take advantage of the higher resolution offered by weather radar data to better represent the effects of rainfall variations on runoff, particularly for convective storms and for complex catchments containing many control structures e.g. urban catchments. However, this type of model remains a research tool; for example, project W242 "Comparison of rainfall runoff models for flood forecasting, EA 2000" recommended further research using this type of model for real time flow forecasting of the impacts of convective rainfall events. Recent developments in weather radar signal processing (Cyclops), rainfall forecasting products (e.g. Nimrod), and related products (e.g. MOSES) mean that rainfall, snow cover and soil moisture data will soon be available in all Agency Regions at a much higher spatial and temporal resolution than in the past. A review is required of the model structures etc which could take advantage of this new high resolution data, and a comparative study performed on several typical catchments with results obtained from simpler lumped or semi distributed rainfall runoff models, particularly during thunderstorm rainfall events and in urban catchments with complex drainage pathways and influences from flow control structures. Studies should include evaluation under real time operational conditions, taking account of the types and quantity of real time monitoring required to support calibration and verification of this type of model.

Main Outputs / User / Benefits
Technical report on the performance of distributed rainfall runoff models under real time operational conditions
Flood forecasting and warning staff
Better understanding of the potential of distributed models in flood forecasting for complex catchments and thunderstorm events

Timescale / Costs / Costs by year: 12 months £95k

Other Funders (internal or external)?
Water Companies and the Met Office may be interested in joint funding this work.

PREPARED BY: Andrew Grime
e-mail address: andrewgrime@weetwoodservices.demon.co.uk

Which one of the following types of R&D would this project come under:

Operational	Policy	Strategy

Which would be the main EA Theme that this project would come under:

Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife

Principal DEFRA / EA Theme: Flood Forecasting & Warning

TITLE: *RAINFALL RUNOFF AND OTHER MODELLING FOR UNGAUGED/LOW BENEFIT LOCATIONS*		
Purpose (Key Customer) - Why is the R&D needed? Ungauged and low benefit locations present a particular problem when a flood warning service is required and most Regions currently only implement a general Flood Watch service. However, there are several technical possibilities for offering a more targeted service which would form the basis of this research e.g. adapting FEH techniques for real time use, rainfall runoff modelling using parameters based on catchment characteristics, and probabilistic/statistical techniques making use of instrumentation in neighbouring catchments.		
Summary (Overall) Objectives To develop and evaluate improved techniques for flood forecasting at ungauged and low benefit locations with the aim of providing a more targeted/technically sound flood warning service at such locations.		
Context (Background) A common flood forecasting problem which arises is that a new or improved flood warning service is required for a Flood Warning Area, but there is no river level instrumentation in the catchment either at or above the location at which warnings are required. Even if instrumentation could be installed immediately, it could take several years to collect suitable calibration data, and there might be technical or economic reasons which rule out any such installation (e.g. low benefit/low risk flooding problems). At present, only a general Flood Watch service can be offered in this case but real time models provide the potential to offer a more targeted service. Possible techniques could include real time application of Flood Estimation Handbook techniques, and transference of model parameters (e.g. for conceptual models) from nearby or analogue catchments. The work could also include development of probabilistic/statistical techniques which estimate the likelihood of flooding in a catchment based on catchment response, meteorological understanding, and the observed response in neighbouring catchments and raingauge/Nimrod etc observations and forecasts of rainfall. The benefits afforded by improved weather radar rainfall estimates (actual and forecast) and soil state (MOSES) could be explored. This project could link into the Next Generation Distributed Rainfall Run-off Models project		
Main Outputs / User / Benefits Research report and guidelines on forecasting techniques for ungauged/low benefit locations Flood forecasting and warning staff Possible extension of flood warning coverage based on technically sound principles		
Timescale / Costs / Costs by year: 12 months £90k		
Other Funders (internal or external)? Recognising that this project would also benefit non-main river sites DEFRA may wish to contribute. There is also synergy between this proposal and ongoing work by CEH under FD2106 National River Catchments Flood Frequency Method Using Continuous Simulation.		
PREPARED BY: Andrew Grime e-mail address: andrewgrime@weetwoodservices.demon.co.uk		
Which one of the following types of R&D would this project come under:		
Operational	Policy	Strategy
Which would be the main EA Theme that this project would come under:		
Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife
Principal DEFRA / EA Theme: Flood Forecasting & Warning		

TITLE: *BEST PRACTICE IN TRANSFER FUNCTION RAINFALL-RUNOFF MODELLING*

Purpose (Key Customer) - Why is the R&D needed?
Transfer function models are used operationally by several Agency Regions for real time flood forecasting but further research is required to develop best practice guidelines on the selection and use of these models; particularly regarding estimation of effective rainfall and choice of model structure.

Summary (Overall) Objectives
To research alternative model structures and ways of using real time data in order to develop best practice guidelines to assist flood forecasting practitioners in the selection, calibration and operation of transfer function models for real time flood forecasting

Context (Background)
Although transfer-function models have been used in various guises by the Agency for the last twenty years, the structure, identification, calibration and application of the models varies greatly. Research is required to identify best practice in terms of transfer-function model structure, calibration (including parameter estimation algorithms), input data (total rainfall or effective rainfall), calibration for a specific lead time, and updating methods (state and parameter). An objective inter-comparison on test catchments is suggested as a suitable way forward with key themes being automated updating of forecasts (as opposed to the manual procedures used at present in some models), and procedures for estimating effective rainfall from total rainfall. The aim would be to review existing approaches, to estimate the accuracy and uncertainties in the proposed modeling approaches, and to explore whether generalised non-linear relationships can be developed for a range of different catchment types based on catchment soil/geological characteristics, current flows, and a range of antecedent conditions (possibly obtained via the new MOSES product). A standard set of non-linear filters that could be used as an 'off-the-shelf' real-time tool would improve forecast quality and consistency.

Main Outputs / User / Benefits
Technical report and guidelines on best practice in transfer function modelling
Flood forecasting and warning staff
Consistent approach to use of transfer function models for flood forecasting

Timescale / Costs / Costs by year

Other Funders (internal or external)?

PREPARED BY:
e-mail address:

Which one of the following types of R&D would this project come under:

Operational	Policy	Strategy

Which would be the main EA Theme that this project would come under:

Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife

Principal DEFRA / EA Theme:

TITLE: *EVALUATION OF NEW APPROACHES TO RAINFALL RUNOFF MODELLING*		
Purpose (Key Customer) - Why is the R&D needed? Despite many decades of research, the problem of estimating the non linear response of river flows to rainfall remains one of the most challenging in hydrology, with uncertainties arising from both the input rainfall data and variations in the catchment response. The Agency needs to remain aware of new approaches and to periodically review their potential for operational use compared to those techniques used at present.		
Summary (Overall) Objectives To review new and emerging techniques for rainfall runoff modelling in the UK and internationally and to evaluate their performance on a number of representative test catchments.		
Context (Background) Rainfall runoff models play a key role in flood forecasting by using rainfall data and forecasts to extend the lead time of flood forecasts. The two main techniques used operationally at present are conceptual models and transfer function models but the Agency has also funded a limited amount of research into newer (but not necessarily better) techniques such as neural network models, and other techniques such as fuzzy rule-based models and nearest neighbour forecasting have been identified as having potential. A review and comparative study of these and other emerging techniques is required to evaluate their potential for real time flood forecasting and to compare their ease of use/calibration with current procedures.		
Main Outputs / User / Benefits Research report on new approaches to rainfall runoff modelling Flood forecasting and warning staff Possible identification of improved methods for real time modelling		
Timescale / Costs / Costs by year		
Other Funders (internal or external)?		
PREPARED BY: e-mail address:		
Which one of the following types of R&D would this project come under:		
Operational	Policy	Strategy
Which would be the main EA Theme that this project would come under:		
Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife
Principal DEFRA / EA Theme:		

TITLE: *REVIEW OF HIGH LEVEL TARGETS FOR FLOOD FORECASTING*

Purpose (Key Customer) - Why is the R&D needed?

The Agency has set targets for the Accuracy, Reliability and Timeliness of flood warning systems but these targets relate to performance of the whole system (detection, dissemination, modelling) and further work is required to interpret (and possibly revise) these targets in a way which is useful to practitioners involved in designing real time modelling systems. In particular, Accuracy targets need to be defined in a more precise way to take account of the forecasting problem, the level of risk/consequences of flooding, and the target audience for flood warnings (public, professional partners, Agency operational staff etc).

Summary (Overall) Objectives

To review and possibly rationalise the Agency's targets for flood warning to meet the needs of real time modellers and to produce best practice guidelines for practitioners how these targets relate to the design of the modelling component of systems, and those which relate to performance of the whole flood warning system. Also, to advise on how best to design real time modelling systems to meet these revised targets.

Context (Background)

The Agency sets a number of high level targets for the Accuracy, Reliability and Timeliness of flood forecasting systems but some fundamental problems faced by practitioners responsible for designing real time models for these systems include:

The targets relate to performance of the whole warning system (including dissemination, telemetry etc) and do not relate specifically to the real time modeling component

Some parameters (e.g. reliability) by definition cannot be estimated at the design stage meaning that a system cannot be designed to meet the required performance

Also, although the targets for Reliability and Timeliness are well understood, further work is required to set appropriate targets for Accuracy depending on the target audience (the public, professional partners etc), the consequences of flooding, and the type of forecasting problem. A thorough review is required of both the definitions of these targets, and their values, with particular emphasis on how practitioners can estimate future performance relative to targets at the design stage, rather than only in post event analyses.

Main Outputs / User / Benefits

Guidelines and technical report on flood warning targets and (possibly) recommended improvements

Flood forecasting and warning staff

A consistent approach to the design of real time modelling system to meet national targets

Timescale / Costs / Costs by year

Other Funders (internal or external)?

PREPARED BY:

e-mail address:

Which one of the following types of R&D would this project come under:

Operational	Policy	Strategy

Which would be the main EA Theme that this project would come under:

Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife

Principal DEFRA / EA Theme:

TITLE*: FRAMEWORK FOR EVALUATION OF THE PERFORMANCE OF REAL TIME MODELS*

Purpose (Key Customer) - Why is the R&D needed?
Post event analyses provide the route to understanding how real time models perform in operational use, and how model performance depends on model type, catchment type, storm type, experience of the model developer/user etc both regionally and nationally. At present, analyses of this type are time consuming and must be performed in an ad-hoc manner depending on the type of model and related data and forecast archiving facilities. A national framework is required for this type of post event analysis which model developers and operational staff can follow.

Summary (Overall) Objectives
To develop procedures and tools to assist operational staff, model developers and researchers in performing post event analyses of the performance of individual real time models (rainfall runoff, routing etc) which comprise a real time flood forecasting system.

Context (Background)
During a flood event, real time models generate forecasts of future levels and flows but, at present there is no standard approach to post event analysis of model performance and no national or regional databases to support such analyses. This means that it is a time consuming and difficult task for operational staff to evaluate model performance as a basis for future improvements, and in particular to evaluate the performance of individual models within the system, as opposed to the whole system. Also, more wide ranging research studies which compare model performance across the Agency also need to physically obtain the models used (and possibly recalibrate them) and to reconstruct forecasts as best as possible based on the data which was archived during (and after) the event. This necessarily restricts the quality and breadth of analyses which can be performed. A national specification is required for the information which should be archived (and related standards) and on how it can best be analysed and presented, together with development of automated tools to assist operational staff in performing these analyses.

Main Outputs / User / Benefits
Guidelines and tools for post event analysis of real time model performance
Flood forecasting and warning staff, researchers, model developers
Techniques to facilitate post event analysis of real time model performance

Timescale / Costs / Costs by year

Other Funders (internal or external)?

PREPARED BY:
e-mail address:

Which one of the following types of R&D would this project come under:

Operational	Policy	Strategy

Which would be the main EA Theme that this project would come under:

Adapting to Climate change	Reducing Flood Risks	Ensuring the Air is Clean
Using Natural Resources Wisely	Improving Inland/Coastal Waters	Protecting / Restoring the Land
Greening the Business World	Quality of Life	Enhancing Wildlife

Principal DEFRA / EA Theme:

<table>
<tr><td colspan="3">TITLE: <i>DECISION SUPPORT TOOLS FOR REAL TIME MODEL SELECTION</i></td></tr>
<tr><td colspan="3">Purpose (Key Customer) - Why is the R&D needed?
Recent research has led for the first time to a set of model selection guidelines for use by flood forecasting practitioners. The potential now exists to develop the basic logic underlying these procedures in combination with GIS/DTM datasets to develop advanced decision support tools combining information on storm meteorology, catchment response and economics into a single tool to assist practitioners in application of the guidelines.</td></tr>
<tr><td colspan="3">Summary (Overall) Objectives
To develop a prototype intranet based decision support tool to assist flood forecasting practitioners in the application of the real time model selection guidelines developed under project WSC13/5.</td></tr>
<tr><td colspan="3">Context (Background)
A recent research project has developed guidelines on the selection of real time models for use in flood forecasting systems. At present the methods are largely paper-based but decision support software could assist in a number of areas. At the simplest level, an intranet based tool could guide users through the model selection process through a series of ‘question and answer’ screens and forms, with possible solutions suggested based on the user’s responses. The economic aspects (costs and benefits/damage avoidance) could also be included in this procedure. More advanced tools might use a GIS/DTM based approach to guide users on selection of model reaches and suitable sites for instrumentation, for example, to map times to peak and peak flows across the catchment (including ungauged tributaries), and to use simple hydraulic models to show regions in which backwater/tidal effects may be significant. Guidance might also be provided on the likely rainfall distributions and storm-history of the region/catchment, and on likely compliance with high level targets.</td></tr>
<tr><td colspan="3">Main Outputs / User / Benefits
Research report and prototype decision support software
Flood Forecasting and Warning Staff
Further refinement of the real time model selection process for flood forecasting applications</td></tr>
<tr><td colspan="3">Timescale / Costs / Costs by year</td></tr>
<tr><td colspan="3">Other Funders (internal or external)?</td></tr>
<tr><td colspan="3">PREPARED BY:
e-mail address:</td></tr>
<tr><td colspan="3">Which one of the following types of R&D would this project come under:</td></tr>
<tr><td>Operational</td><td>Policy</td><td>Strategy</td></tr>
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<tr><td>Greening the Business World</td><td>Quality of Life</td><td>Enhancing Wildlife</td></tr>
<tr><td colspan="3">Principal DEFRA / EA Theme:</td></tr>
</table>

<table>
<tr><td colspan="3">TITLE: <i>DECSION SUPPORT TOOLS FOR FAST RESPONSE CATCHMENTS</i></td></tr>
<tr><td colspan="3">Purpose (Key Customer) - Why is the R&D needed?
Fast response catchments pose a particular flood risk particularly during thunderstorms. Existing rainfall runoff modelling approaches could possibly be supplemented by ‘first alert’ systems which rely on recognising combinations of conditions and trend which may lead to flood conditions.</td></tr>
<tr><td colspan="3">Summary (Overall) Objectives
To review international approaches to flash flood forecasting and to evaluate and demonstrate their application under UK conditions for several representative high risk (e.g. urban) catchments.</td></tr>
<tr><td colspan="3">Context (Background)
Fast response catchments pose a particular flood risk due to the short lead times available to disseminate warnings. This is particularly the case for thunderstorm generated events, which may develop over time periods of an hour or less. The classical approach of feeding rainfall data and forecasts into rainfall runoff models provides one way of forecasting possible flooding, but requires interpretation and, possibly, intervention by Flood Warning staff to make use of the information provided. This presents operational problems regarding alerting staff to fast response events, particularly when they occur ‘outside’ the usual flood season e.g. in summer. Several other countries (e.g. the USA, France) are investigating more automated web based approaches to flash flood forecasting, in which rapid decisions can be taken on flash flood potential based on catchment characteristics and conditions, trends in radar rainfall data, probabilistic and Monte Carlo assessments of risk, pattern recognition of combinations of conditions which might lead to flooding or have led to flooding in the past. These methods, combined with research into how to include the warnings provided into operational procedures, possibly also have potential in the UK</td></tr>
<tr><td colspan="3">Main Outputs / User / Benefits
Research report and prototype decision support software
Flood Forecasting and Warning Staff
New approaches to supplement existing modelling procedures for fast response catchments</td></tr>
<tr><td colspan="3">Timescale / Costs / Costs by year</td></tr>
<tr><td colspan="3">Other Funders (internal or external)?</td></tr>
<tr><td colspan="3">PREPARED BY:
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<tr><td colspan="3">Principal DEFRA / EA Theme:</td></tr>
</table>

APPENDIX D

Factsheets – Flood Forecasting Issues

Method	**Factsheet**	**Region**	**River/location**
Fast Response Catchments	FF1	North East	Upper Calder
	FF2	South West	Sid
	FF3	Wales	Afon Clun
Confluence Flooding	FF4	Southern	Yalding
	FF5	North East	Ure
	FF6	Thames	Loddon
Influence of Structures	FF7	North East	Don
Low Benefit Locations	FF8	Anglian	East Suffolk rivers
		Wales	Teifi
		Midlands	Leam
Floodplain Storage	FF9	North East	Tees
Groundwater Flooding	FF10	South West	Avon
	FF11	Anglian	Slea
Urban Catchments	FF12	Thames	Ravensbourne
		Midlands	Tame
Reservoired catchments	FF13	Wales	Afon Rheidol
	FF14	Anglian	Eyebrook
Complex channels/catchments	FF15	South West	Tone
	FF16	Thames	Thames
	FF17	Thames	Lower River Colne

Note:
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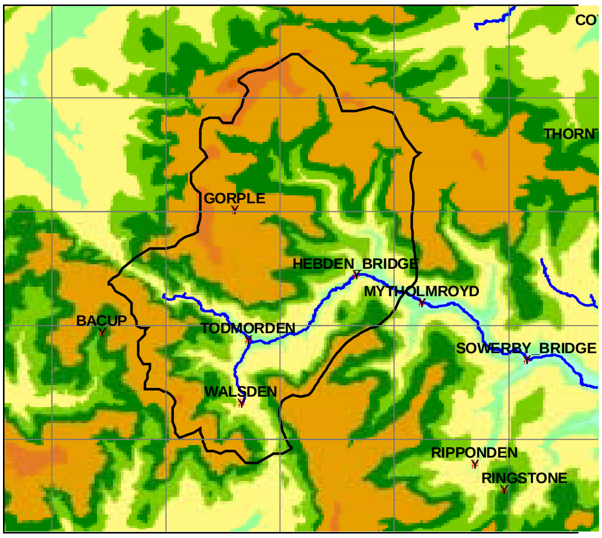
FF1. FAST RESPONSE CATCHMENTS

North East Region: Upper Calder

The Upper Calder flows through steep and narrow valleys on the south-eastern edge of the Pennines past several towns including Hebden Bridge, Todmorden, Walsden Mythomroyd.



The main forecasting issues are the rapid response of the river to rainfall and the proximity of the flood risk areas to the head of the catchment. Problems also arise from potential flooding due to snow-melt and from localised thunderstorms.

Flood forecasting techniques used are either empirical (trigger levels) or rainfall-runoff and hydrological routing models. Trigger levels are based on levels at upstream gauging stations and a reactive approach is often taken when setting thresholds. For example as a result of the failure of structures in the June 2000 Calder floods, amendments were made to the trigger levels at Todmorden and Walsden gauging stations.

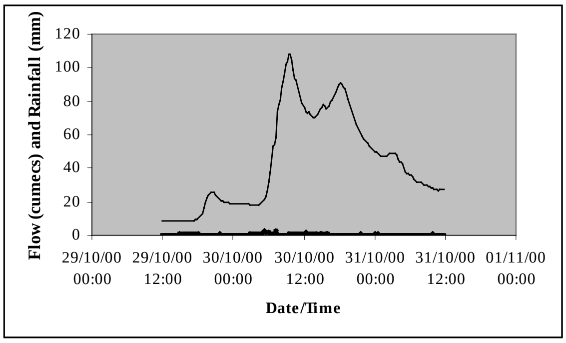


Figure 1: October 2000 event at Mytholmroyd

The RFFS (Regional Flood Forecasting System for the North East) contains PDM and kinematic wave components for the Upper Calder. However the PDM models need to be recalibrated using weather radar rainfall data if quantitative precipitation forecasts are to be used as a model input. The Upper Calder has some reasonable rainfall and level gauges, but there are no flow gauging stations.

FF2. FAST RESPONSE CATCHMENTS

South West Region: River Sid

The river Sid drains a small catchment to the north of Sidmouth. It rises at 205m above sea level and flows for about 5.5 km through a narrow, steep sided valley, through Sidbury and Sidford, before passing through Sidmouth to its outfall to the English Channel.

The main forecasting issues are the rapid response of the river to rainfall and the proximity of the flood risk areas to the head of the catchment. Time to peak to Sidbury is only 1.25 - 2.75 hours, while the travel time between here and Sidmouth is only about 0.5 - 1 hour. Time to peak graphs have been produced for the catchment, which, while they are not used in real time, are used to develop an understanding of flood behaviour within the catchment.

Flood forecasting techniques used are trigger levels based upon the levels throughout the catchment. Forecasting in this catchment is further complicated by the lack of a flow gauge in the upper catchment. There is a level gauge at Sidbury, which could be developed for forecasting purposes. The following options could be investigated:

- Simple empirical relationships based upon catchment wetness index and rainfall depth and duration for the gauge at Gittisham compared to the river level gauge at either Sidford or Sidbury.
- Develop a rainfall-runoff model of the catchment. This model would be calibrated to the river level gauge at Sidbury, which would be converted to flow via a rating. The flood level in Sidmouth would be predicted using either:
- A level to level correlation between the gauges at Sidbury, Sidford and the tidal outfall;
- A straightforward relationship between flow and maximum defence scheme capacity, which is set at 40m^3/s (1 in 30 years).
- Run the above rainfall-runoff model during dry periods to establish the likely flood impact of different combinations of catchment condition, rainfall depth and duration. This risk matrix could then be used in real time to predict flooding based upon catchment and rainfall conditions.
- To increase lead-time to the statutory required for a major incident plan (4 - 6

hours) rainfall forecasting could be applied to either the empirical relationships or the models.

A rating has been developed for the level gauge at Sidbury, but this needs to be improved by developing another rating at a closest available river constriction (small bridge) to check.

FF3. FAST RESPONSE CATCHMENT

Wales: Afon Clun

The Afon Clun is a major tributary of the Afon Ely, draining an area of 32km^2 to the north-west of Cardiff in the south-east area of EA Wales. The underlying geology is primarily sandstone and an escarpment bisects the catchment. The elevation ranges from 240 m to approximately 45 m AOD at the confluence with the Ely. Approximately 18% of the catchment is defined as urban.

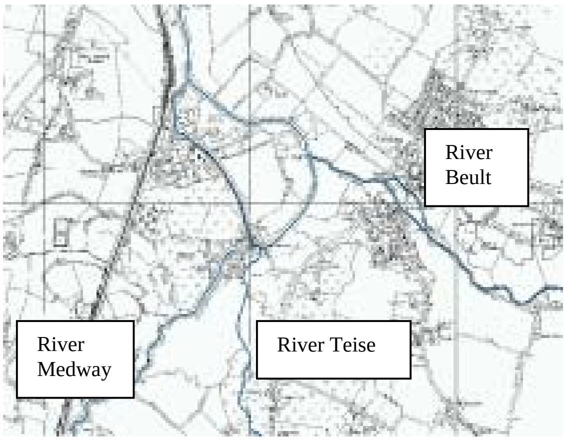
The steep slopes, shallow soils, large urban areas and high rainfall totals give rise to a catchment with a rapid response to rainfall and flooding problems throughout. Flooding at the confluence is also an issue when the river levels in the Afon Ely are high.

A combined MIKE11 conceptual rainfall-runoff and hydrodynamic model developed for flood risk mapping could be converted to a real-time implementation for forecasting purposes.

A catchment with a short response time requires a rainfall-runoff model, which is able to use observed and/or forecasted rainfall to provide sufficient lead time for flood warning, whilst the application of a hydrodynamic model will ensure that flood levels and extents throughout the catchment and at the confluence are accurately predicted.

FF4. CONFLUENCE FLOODING

Southern Region: Yalding



The town of Yalding in Kent, is just downstream of the confluence of the rivers Medway, Teise and Beult. The Upper Medway and the Teise have their headwaters in south-west Kent and south-east Sussex while the River Beult rises on wealden clays in Kent.

Heavy rain during 9th – 11th October 2000, falling onto already wet catchments, caused severe flooding in this area. In Herstmonceux in East Sussex, 103 mm of rain fell in the three day period from 9th – 11th October, rainfall with a nominal return period of 50 years. For the UK as a whole, October 2000, was the wettest October since 1903: rivers overflowed their banks in many areas with extensive inundation of floodplains, some of which remained under water for several days or weeks. Many towns and villages within or on the edges of the floodplains were severely affected by the floodwater, often to depths greater than previously experienced by local residents. The smaller, upland catchments were the first to react to the heavy rainfall with villages such as Lamberhurst on the Teise and Robertsbridge on the Rother suffering. Edenbridge on the River Eden, an upper tributary of the Medway in West Kent, came within centimetres of major flooding with water lapping at the crest of the floodwalls for several hours. A similar situation occurred at Smarden on the River Beult.

The Leigh Barrier across the floodplain of the Medway was manned from early on 9th October, with excess flood water being impounded from October 12th, flooding the valley and reducing the volume of water passing through Tonbridge. The barrier was continuously manned by Agency staff for six days until the evening of 14th October. The severity of flooding at Tonbridge, Yalding and the villages downstream was significantly reduced by this operation.

Beyond the protection of the Leigh Barrier, downstream of Tonbridge, the village of Yalding adjacent to the confluence of the Beult, the Teise and the Medway was severely affected by flood water for two or three days (see photo).

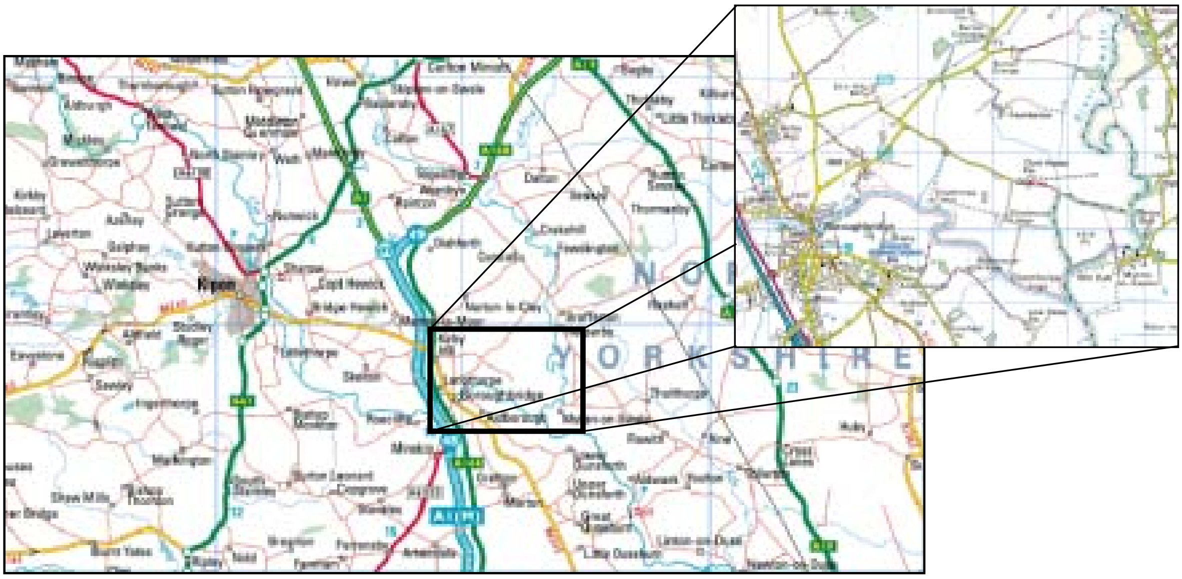
The flooding in Yalding on October 9th – 12th, while less extensive than if the Leigh Barrier had not been operating, still caused widespread flooding throughout the town. Levels through the middle of the town were sufficiently high to flood over 150 properties, generated by the combination of the high flows from all three rivers exceeding the conveyance capacity of the channel.

Many residents considered that the severity of the flooding was exacerbated by the lack of dredging of river channels over recent years and failure to clear field drains and culverts both during and prior to flood events (Environment Agency, 2001, Autumn 2000 Floods Review, Kent Area).

FF5. CONFLUENCE FLOODING

North East Region: River Ure

Boroughbridge is situated on the River Ure in the North-East Region of the Agency. The Ure drains a catchment area of approximately 930km^2 to Boroughbridge. The confluence of the Ure and the Swale is approximately 5km downstream of the town and flooding can be caused by backing up of flood water as a result of high levels in the Swale.



Current Forecasts at Boroughbridge are either:

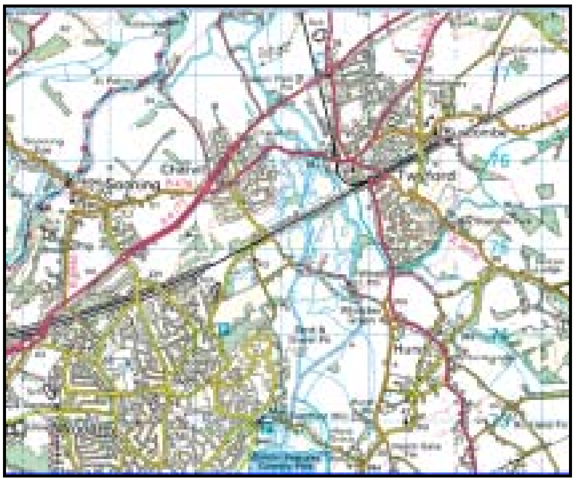
- Empirical relationships based on upstream levels reached at Kilgram and Ripon gauges on the Ure and Swale respectively.
- From the RFFS. The RFFS for the River Ure contains PDM and kinematic wave components, and also a level to level correlation component. A hydrodynamic model also exists, but this has not been converted to real-time.

The use of rainfall-runoff and routing models cannot accurately predict the behaviour of a confluence under conditions of high flow impoundment. To model confluence flooding accurately requires the use of an HD model. However, if flooding at this confluence is relatively predictable and related to flows and levels in the Swale, then simple level to level correlation might be used to predict flood levels.

FF6. CONFLUENCE FLOODING

Thames Region: River Loddon

The River Loddon (Thames Region) rises on chalk in the area around Basingstoke and flows for over 45km to its confluence with the Thames near Wargrave.



There are two main flooding issues:

- at the confluence with the Thames, there is insufficient channel capacity, which causes overtopping during high flows and properties may be at risk from the Loddon, the Thames or a combination of both.

- the lower reaches of the Loddon are noted for a large number of historic mills around which localised flooding can occur.

The uncertainty of the flooding processes makes it difficult to forecast the need for warnings.

The confluence area of the River Loddon and Thames was identified in 1995 by the NRA as the most significant area of flood risk in the catchment. During flood events high river levels in the Thames cause backing up of flows in the Loddon, which results in long duration flood conditions. For example in January 1990 a number of houses were flooded to a depth of 0.1 to 0.25 m for several days. There are good flow and level data and reasonable rainfall data available for the Thames and Loddon catchments.

Current forecasting is based on trigger level thresholds. There is a hydrodynamic model of the Thames, which is currently being converted to real time use. However no model exists of the Loddon.

In order to forecast flooding at the confluence, a model would be required for the flows along the River Lodden and the levels in the Thames. It is possible that a simple relationship would be very applicable in this situation. If reliable level-to-level correlations can be generated for the Thames, then levels can be predicted in this channel with a lead time of about six hours. A rainfall runoff model can be used to forecast flows in the River Loddon and from a matrix of historical flow and level conditions, expected flood elevations and durations could be determined.

FF7. INFLUENCE OF STRUCTURES

North East Region: River Don

In the River Don catchment there are five river regulators used to direct flow into washlands in order to reduce peak flows at Doncaster. These are manually controlled, and although there are procedures, structures are generally opened and closed based on the experience and judgement of the operators. It is therefore difficult to apply ‘what if’ modelling with so many variables.

In the RFFS the Upper Don is represented using PDM and KW models. Ideally, a flood forecasting model would include an allowance for the structures, but it is not possible to predict exactly how they will be operated.

FF8. LOW BENEFIT LOCATIONS

(i) Anglian Region: East Suffolk Rivers

The area of east Suffolk between the Waveney and the Gipping is drained by half a dozen small rivers (catchment areas not exceeding 150 km^2) including the Alde, the Hundred, the Yox, the Blyth and the Wang. Each of these rivers drain fast reacting, Boulder Clay, catchments. The population of the area is low in number and dispersed into a large number of small hamlets and villages.

Flood risk in the area is very real. In 1993 the villages of Debenham and Wrentham suffered severe flooding.

The key forecasting problem for the area is that there are a large number of flood risks, each often affected by a different river. When considered individually the flood risks are difficult to justify a significant investment in flood forecasting. However when considered as a group there is a significant forecasting need that requires addressing.

Flood warnings for the area are currently issued based on trigger levels at the nearest gauging stations. The gauges are often some distance from flood risk areas, and frequently in different catchments. During localised events it is possible either that flood warnings are not issued (as storms effect a flood risk zone but not the catchment draining to a trigger gauge) or that false alarms are raised.

(ii) Wales: River Teifi

The River Teifi drains approximately 800km^2 in South West Wales, and isolated properties are at risk of flooding. There is a poor correlation relationship between three level gauges because of the variability of rainfall in time and space, the catchment shape and the existence of a raised peat bog in the upper catchment. It is also difficult to forecast when the upstream on-line reservoir will fill.

The current forecasting procedures include the use of an in-house hybrid rational/rainfall runoff model. The catchment has good rainfall and level data, and reasonable flow data available (FEH only identifies 2 flow gauges, and the records from one are to be treated with caution).

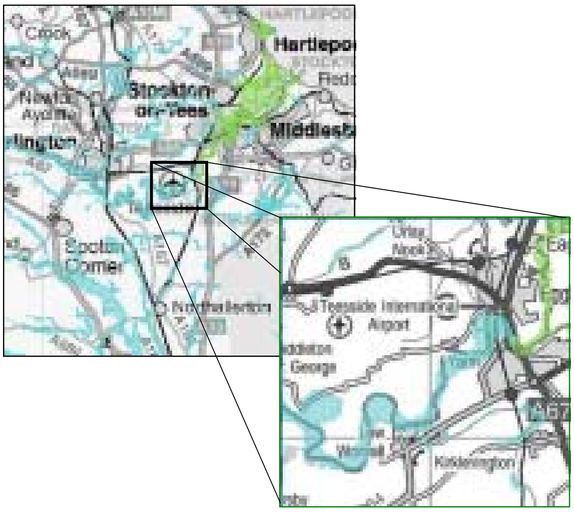
(iii) Midlands Region: River Leam

Only nine properties on the River Leam (Midlands Region) were thought to be at risk of flooding, and this was therefore deemed a low benefit location. During the floods of Easter 1998, extensive flooding occurred and, although a 5 hour lead time was provided, the warning infrastructure was not in place. New good quality gauges have now been installed to improve the service.

FF9. FLOODPLAIN STORAGE

North East Region: River Tees

The River Tees has a total catchment area of over 2000 km^2, which rises in the hills of the northern Pennines and flows east to Stockton and Middlesborough. It has two major tributaries in its lower and middle reaches, the Skerne and the Leven. The catchment contains very significant floodplain areas in the lower reaches, which strongly influence the forecast of flood levels for the urban centres downstream.



The (now superceded) model of the River Tees was based around a set of kinematic wave routing models. These do not represent floodplain storage at all and hence were not successful at forecasting flood levels on the lower river.

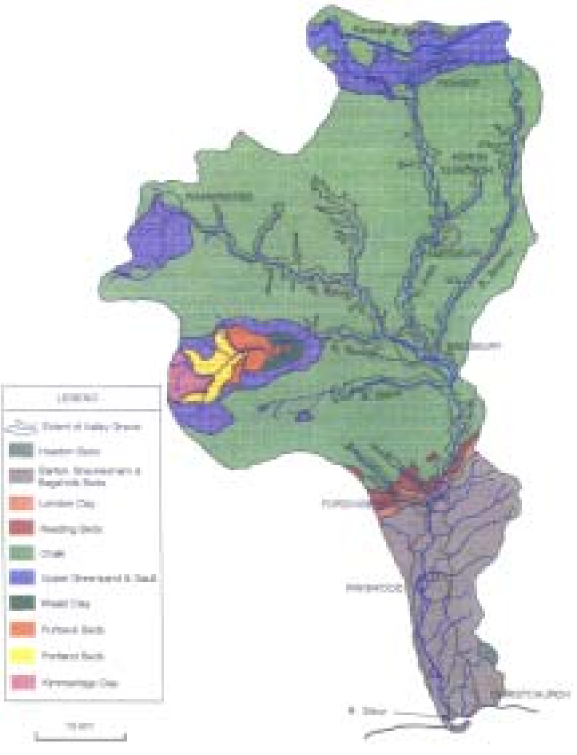
These problems have been resolved by the implementation of real time hydrodynamic model. This HD model was originally built to assist in the design of the Tees Barrage and has been modified in order to use in real-time and added into the RFFS as a component. The forecasting model of the River Tees consists of rainfall-runoff models for the Upper Tees, kinematic wave routing models for the middle reaches and a HD model for the lower section. The model has not been tested for a large event as yet, but early results are encouraging.

FF10. GROUNDWATER FLOODING

South West Region: River Avon

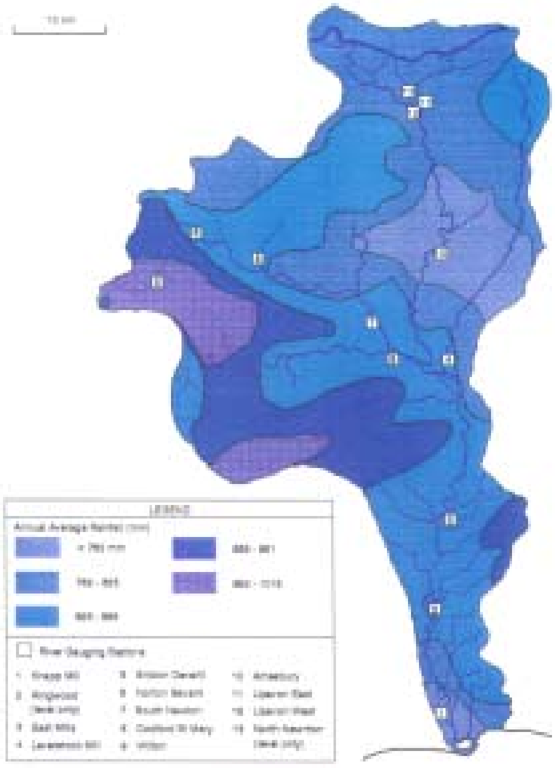
The Hampshire Avon is a large chalk dominated catchment rising in the hills to the north of Salisbury, flowing through the town and down to its outfall at Christchurch. The catchment area is over 1700 km^2 and includes the rivers Avon, Bourne, Wylye, Nadder and Ebble.

The rivers are largely spring fed from the large chalk block on which they rise and this gives rise to significant groundwater flood risk. The geology is illustrated on the following map.



The main forecasting issues are the relatively slow increase in groundwater levels generating high spring flow values, and groundwater flooding. Groundwater generated floods are significant and the flood risk to major urban centres is great. The highest recorded flow was observed by flow gauging on 1st November 1960 at Fordingbridge on the lower Avon, and measured 116 m3/s.

Long lead times should be available and forecasts could be generated from telemetered groundwater levels.



If boreholes throughout the catchment were telemetered, then the levels in these could be correlated to the river flow at various points throughout the catchment (see map below for network of flow gauges) and predictions of river flow could be made based upon groundwater level.

The large catchment area means that groundwater levels are likely to be relatively slow to react to rainfall and by creating correlations throughout the catchment, from the upper reaches, through Salisbury, to the outfall, flow predictions should be possible for the whole area.

A set of rainfall-runoff models could also be developed to provide a further forecasting capability during the scenario of full groundwater stores and surface runoff being the main factor causing flood flows.

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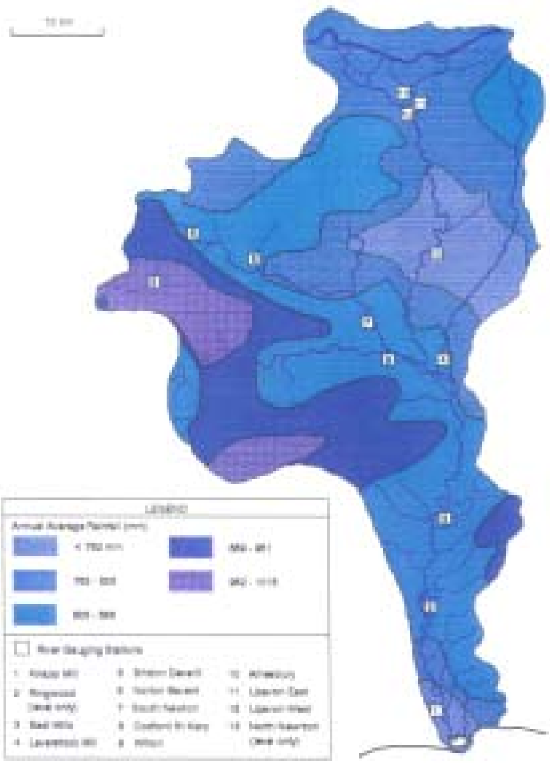


A set of rainfall-runoff models could also be developed to provide a further forecasting capability during the scenario of full groundwater stores and surface runoff being the main factor causing flood flows.

FF11. GROUNDWATER FLOODING

Anglian Region: River Slea

The River Slea, a baseflow dominated catchment draining part of the Lincolnshire Limestone ridge south of Lincoln, was modelled by WS Atkins as a sub-catchment of the Witham flow forecasting model, a pilot for the Anglian Flow Forecasting System. Two approaches were considered to represent runoff from the catchment:

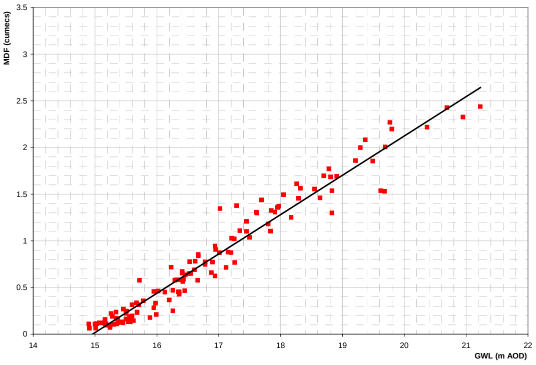
- conceptual rainfall-runoff modelling
- combined conceptual rainfall-runoff modelling and a regression between groundwater levels and average daily flows. The rainfall-runoff models simulating surface runoff and inter-flow and the regression simulating baseflow.

Although the conceptual rainfall-runoff modelling approach provided a conceptually sound and flexible framework within which to undertake the calibration of the catchment model, the method has two key disadvantages.

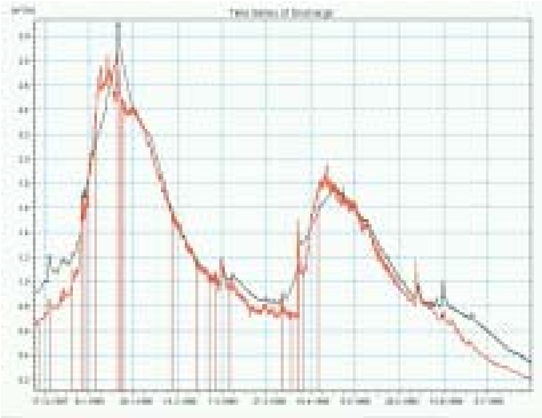
- it was difficult to represent the complex groundwater processes of the catchment using simple lumped rainfall-runoff models.
- the rain gauges available for use in the model calibration period were unsuitably located and had sporadic records (when using a continuous rainfall-runoff models to simulate baseflow dominated catchments, an unbroken rainfall input is imperative in order that the model stores are sustained).

Following trials it was decided to adopt the mixed rainfall-runoff / groundwater regression approach. The groundwater regression was developed to allow flow at time *t* to be forecast from groundwater levels at time t – 5 days.

The regression between groundwater levels at Leasingham Borehole with flow at Leasingham gauging station is shown in the following figure.



The model calibration achieved using this method at Leasingham gauging station is shown in the following figure.



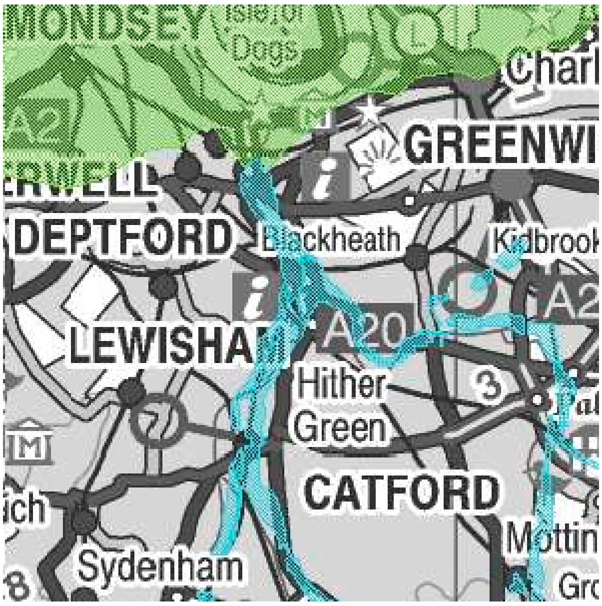
The assumptions, strengths and weaknesses of this approach are presented in the main report.

FF12. URBAN CATCHMENTS

Thames Region: River Ravensbourne

The River Ravensbourne drains an urban area in South London. The river rises to the south east of London on Bromley Common and flows north, through Catford and Lewisham, to its confluence with the Tidal Thames at Blackheath (opposite the Isle of Dogs). The river has a catchment area of only about 150 km^2, the majority of which is heavily urbanised and subject to extremely rapid runoff rates.

Achieving the required lead time of 2 hours is a problem, not only due to the urbanised nature of the catchment, but also since the sudden development of ‘clear air’ convective events means that times to peak can be as short as 1 hour.

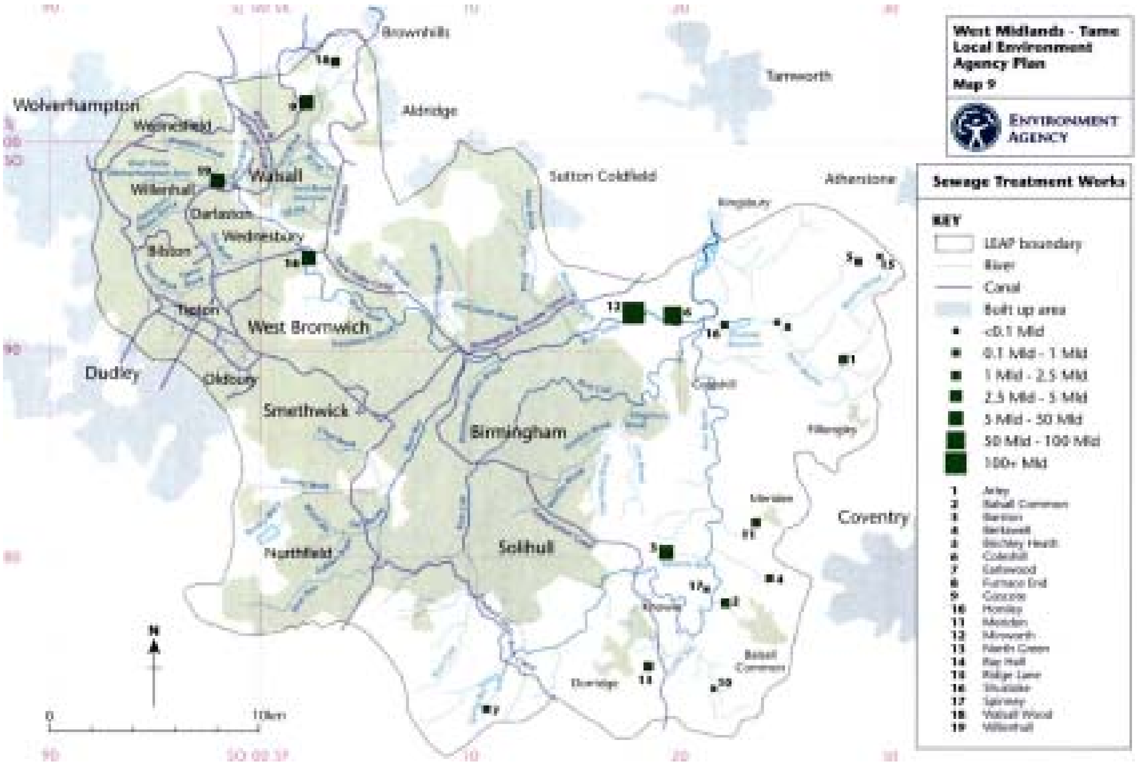


Midlands Region: River Tame

The River Tame drains the major urban area of Birmingham and forms a major tributary of the River Trent. The Tame has a catchment area of 1475 km^2 to the gauging station at Elford, just upstream of the Trent confluence.

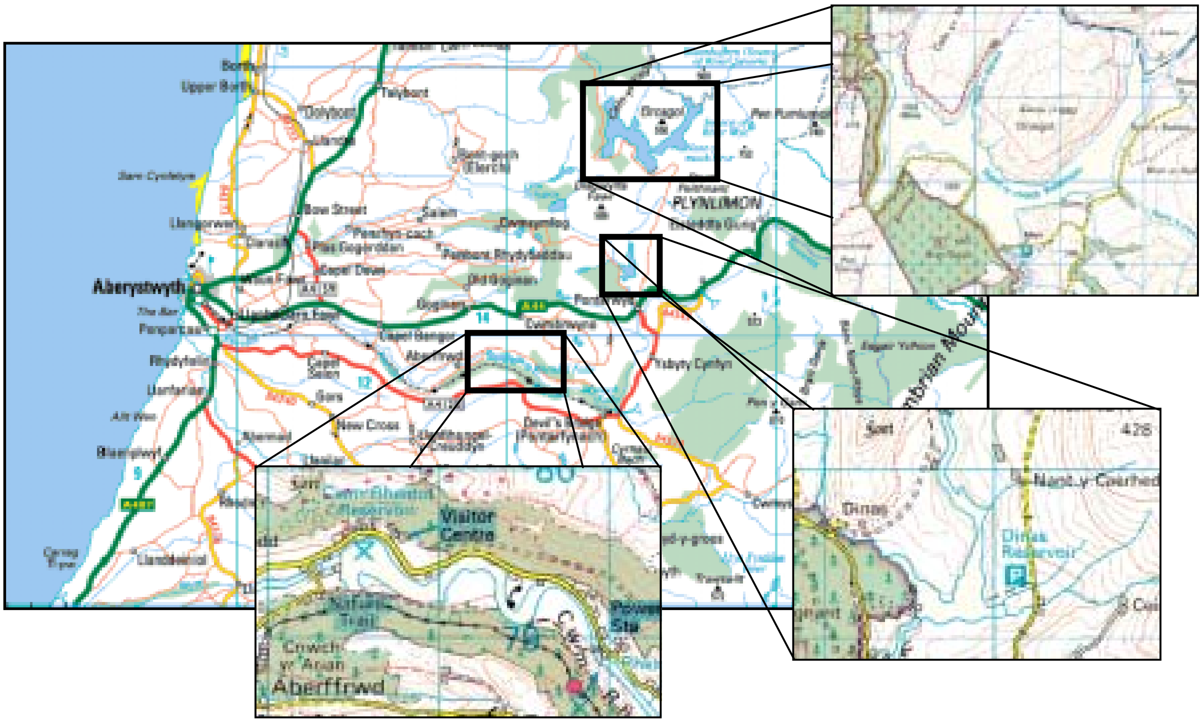
The figure below (from the River Tame LEAP) illustrates the River Tame catchment, and in particular the extent of the urban area that it drains.

Currently, the forecasting approaches for this catchment are a rainfall runoff model applied to each of the sub catchments, and a routing model applied to the main river reaches. The timing of forecasts produced is sometimes poor, particularly during convective events, due to a lack of any physical representation of the urban drainage characteristics and the complexity of the drainage network in this area.



FF13. RESERVOIRED CATCHMENTS

Wales: Afon Rheidol



The River Rheidol rises in the mountains of eastern Wales and drains to the coast at Aberystwyth. The catchment area upstream of Aberystwyth is approximately 185 km^2. The upper catchment is extremely steep, with narrow gorges, and prone to very rapid runoff and short times to peak. The lower catchment, on the other hand, between Cwm Rheidol and Aberystwyth, is flatter with extensive floodplain reaches.

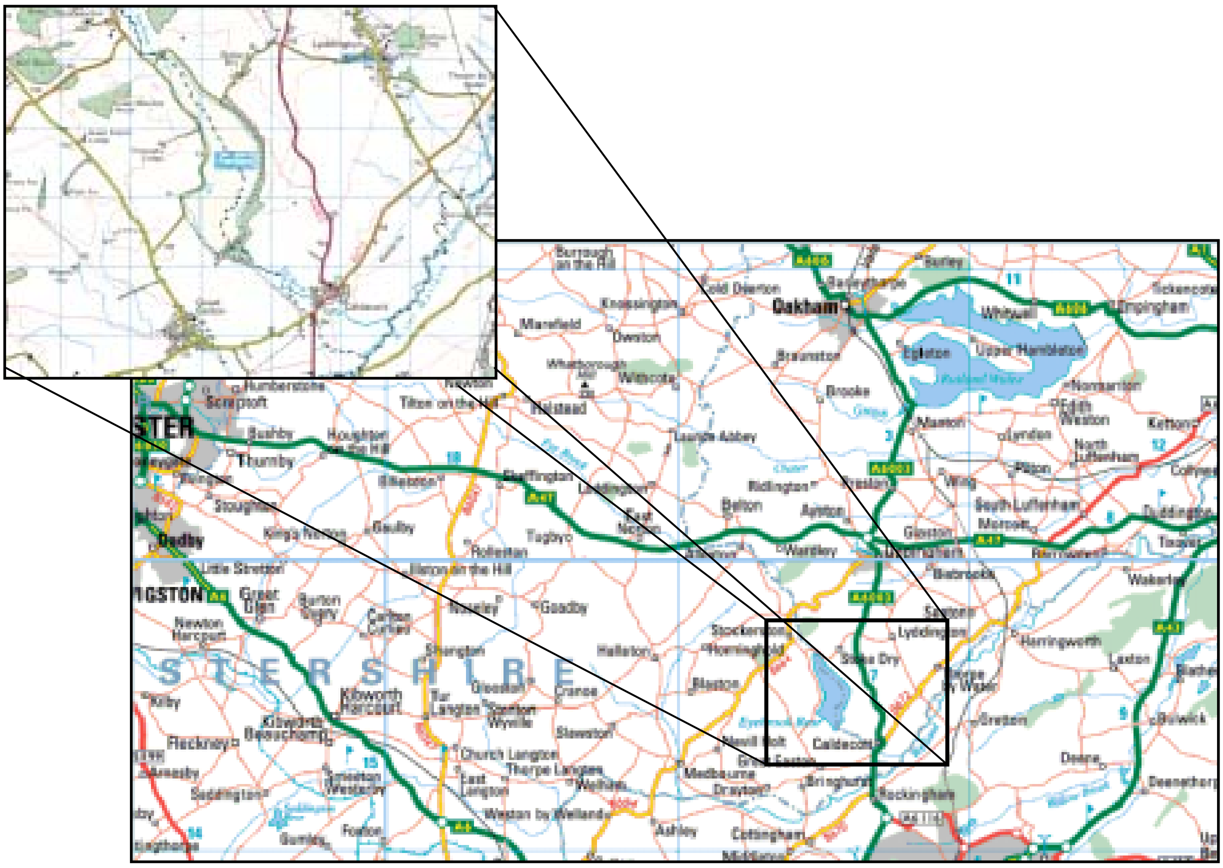
70% of the catchment upstream of the flood risk area of Aberystwyth is part of a linked 3-reservoir hydropower scheme. There is a forecasting threshold for the onset of hydrological runoff between them is required to accurately predict flood flows downstream of Cwm Rheidol in Aberystwyth. A model that accounts for the impact on flood levels of the downstream flooding, but the reservoir storage and operation procedures make forecasting of the magnitude and timing of the peak difficult. An in-house rainfall runoff model exists to assist with forecasting and there are reasonable flow and level gauges and good rainfall gauges in the catchment.

The complexity, and interlinked nature, of the reservoir operation serves to ensure that simple forecasting approaches are unlikely to be successful. A methodology that accounts for the outflow control rules of the dam structures, the combined impact of the operation of all three reservoirs and the

tidal reaches of the river would also be needed.

FF14. RESERVOIRED CATCHMENTS

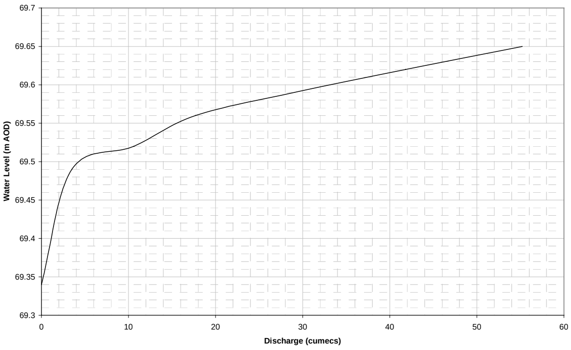
Anglian Region: Eyebrook



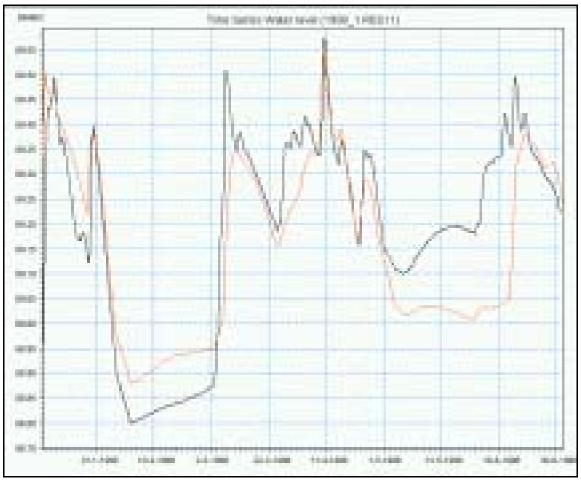
Eyebrook is a major tributary of the River Welland, just to the north of Market Harborough. The upper catchment includes a major water supply reservoir, draining a catchment area of approximately 57 km^2. Outflow from this reservoir is via 16 parallel siphons and a scour valve set just above bed level. The outflow from the reservoir flows into a large flood diversion channel and over two measurement structures: a high flow and a low flow crump weir. The low flow weir measures continual compensation releases (via a pump), and the larger structure measures flood outflow from the reservoir.

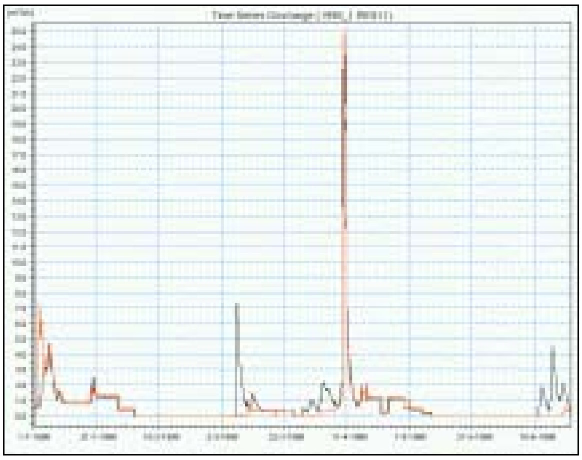
The downstream impact of outflow from this reservoir is very great. The siphons have a very sensitive Q-h relationship (see below) whereby small changes in reservoir level can result in large changes to outflow discharge and hence downstream flood risk.

The reservoir was modelled as part of a catchment model of the entire Welland and Glen system using an explicit 1-D representation. The cross sections for the reservoir were derived so that the stage - storage relationship mimicked reality. This ensured that the outflow for a given reservoir head would be correct.



Inflow to the reservoir was modelled using a rainfall-runoff model, calibrated to observed levels and observed outflow. The siphons and scour valve were modelled hydraulically and the outflow from the reservoir was calibrated to the down stream high flow gauge. The calibration plots are illustrated in the following figures, showing firstly, reservoir level and secondly, outflow discharge.

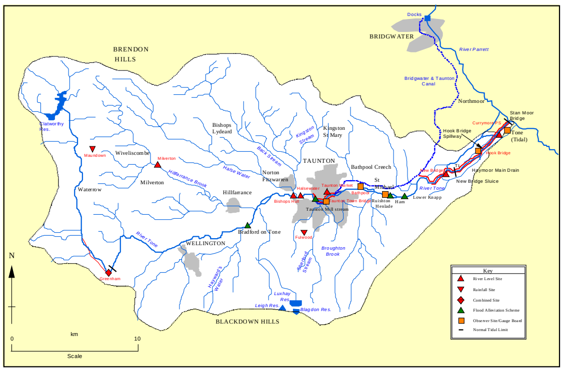




FF15. COMPLEX CHANNELS/CATCHMENTS

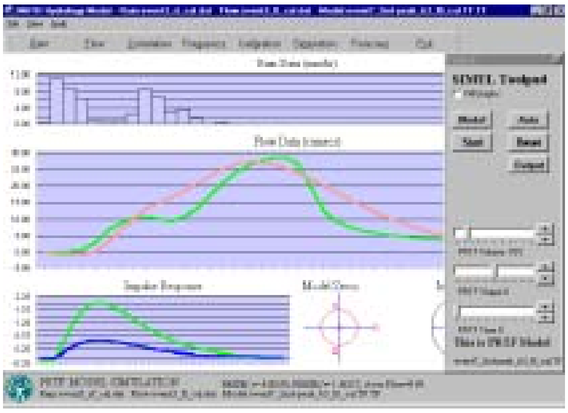
South West Region: River Tone

The River Tone flows from its headwaters at approximately 400m above sea level in the Brendon Hills. The upper 5% of the catchment is dammed at Clatworthy Reservoir, below which the river runs through a steep narrow valley to downstream of Tracebridge. Through and below Greenham, the river opens out considerably and the floodplain is flat and wide with gently rising valley sides. From here the river flows through agricultural land to Taunton and then on through the highly managed, flat, alluvial plains of the Somerset Levels region.

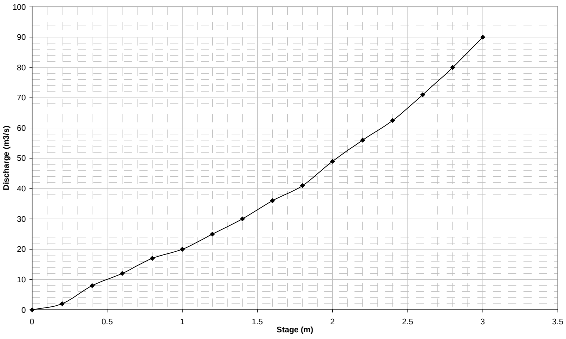


A PRTF rainfall-runoff model has recently been developed which simulates flows to Bishops Hull gauging station upstream of Taunton. The volume, shape and lag parameters of this model can be manually updated either prior to the onset of an event or during an event, and guidelines are being developed to relate these parameters to antecedent catchment conditions to objectify model initialisation. Investigations are also being undertaken the impact of the use of effective rainfall on flow forecasts and on methods of defining effective rainfall.

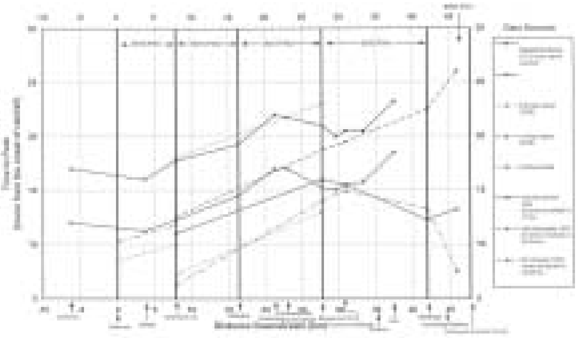
The simulation of an event on the 19th September 1999 is shown in the following figure (observed flow in green/dark grey, and simulated in red/light grey).



The flow at Bishops Hull is converted to a flood level using the rating shown below.



Travel times through the catchment are rapid and derived from the geological make-up of the catchment. Historical observed time to peak (from the onset of rainfall) varies between 6.5 and 18 hours for Greenham and 13 and 23 hours for Bishops Hull. This means that a rainfall-runoff model running in real time would provide adequate lead-time for Taunton even during major incident plans.



At present, the PRTF model is not run in real-time due to time pressure commitments during an event and trigger levels are used as the primary forecasting tool.

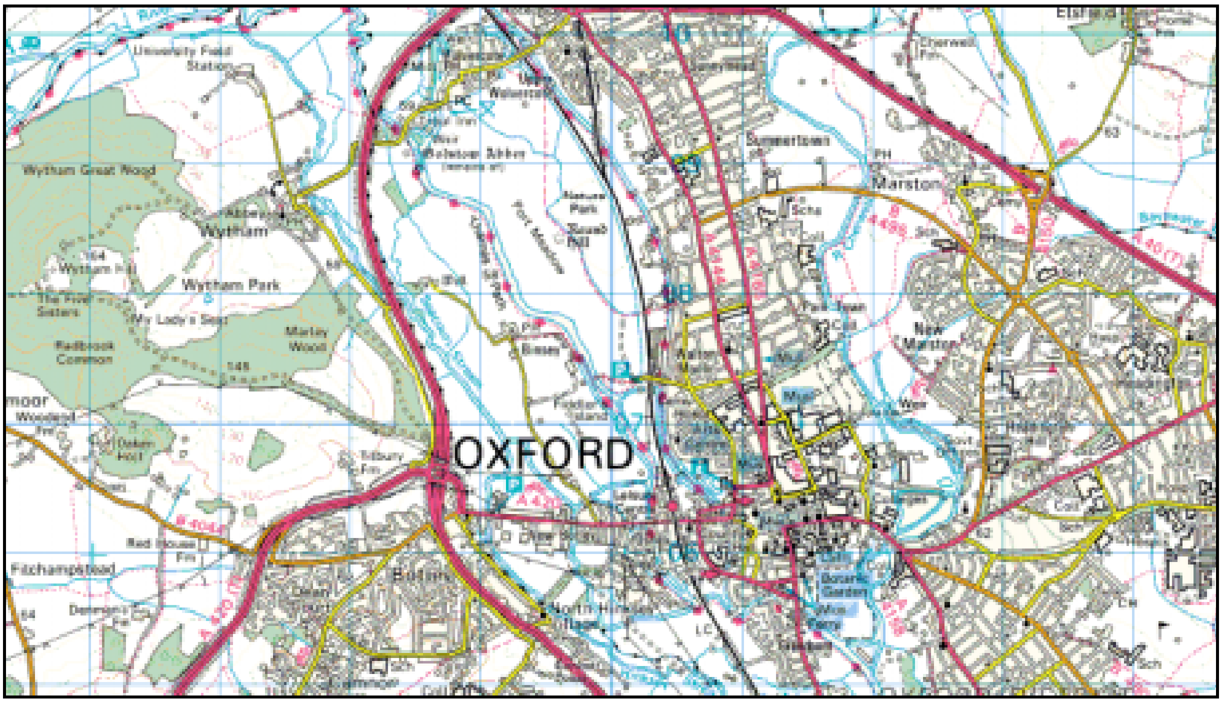
The catchment is extremely complex. A forecast is required for the urban centre of Taunton, using either the PRTF model or a simpler empirical relationship between rainfall at Maundown and Fulwood and stage/flow at Bishops Hull. In addition to this, volume forecasts are required for the Somerset Levels downstream of Taunton so that flooding does not occur in this area due to an overloaded system.

The PRTF model will predict peak flows and levels in Taunton, but the peak of this model does not necessarily represent the time when flood risk is greatest. The continuation of high flows into the Somerset Levels may result in the channels in this area overtopping and this may lead to a catastrophic flood event.

FF16. COMPLEX CHANNELS/CATCHMENTS

Thames Region: River Thames

The River Thames at Oxford splits into a number of different channels as it passes through Oxford and several structures influence these flow diversions. Small increases in level within these various bifurcated channels can result in considerable variations in property flooding. For example in November 2000 no properties were affected, however in December 2000 92 properties flooded with an increase in level of less than 0.1m. The hydraulics of the area are complex due to the interaction of these bifurcated channels and large hydraulic structures and simple forecasting approaches cannot adequately predict levels.


OXFORD
Wytham Great Wood
Wytham
Wytham Park
University Field Station
Summertown
Marston
New Marston
Botley
North Hinksey
Elsfield
Fitchampstead
Radbrook Common
Marley Wood
Godstow Abbey
Wolvercote
Port Meadow
A 420
A 4144
B 4495
A 40 (T)

FF17. COMPLEX CHANNELS/CATCHMENTS

Thames Region: Lower River Colne

Over the downstream 15 km of the River Colne, the channel splits into a large number of bifurcated reaches. Each of these separate channels has its own flooding issues, but the level in each is influenced and controlled by the level in the other interconnected channels. It is, therefore, difficult to forecast flows and levels in each individual channel. As with the River Thames through Oxford, simple forecasting approaches cannot provide a satisfactory answer to these complex issues and mode detailed hydraulic modelling is required to accurately simulate flows and levels through these channels.

APPENDIX E

Factsheets – Real Time Modelling Techniques

Method	Factsheet	Location
Empirical Methods		
Level-Level correlations	RTM1	River Caldew (North West)
Flow-Flow correlations	RTM2	River Irwell (North West)
Time of Travel Maps	RTM3	River Uck (Southern)
Antecedent Precipitation Index	RTM4	General example from the USA
Flood Watch Thresholds	RTM5	Thames and Midlands Regions
Threshold Exceedance tables	RTM6	Great Ouse (Anglian)
Blackbox Models		
Unit Hydrograph	RTM7	Red River of the North – North Dakota, USA
Transfer Function (PRTF)	RTM8	River Greta (North West)
Transfer Function (PRTF)	RTM9	River Tone (South West)
Artificial Neural Network	RTM10	South River Tyne (North East)
Conceptual Models		
MIKE 11 Rainfall Runoff	RTM11	General example
Snowmelt Models	RTM12	North East, Anglian and Midlands
Routing Models		
Hydrological Routing (DODO)	RTM13	Midlands Region
Hydrodynamic (ISIS)	RTM14	River Eden (North West)
Hydrodynamic (MIKE 11)	RTM15	Rivers Welland and Glen (Anglian)

Note:
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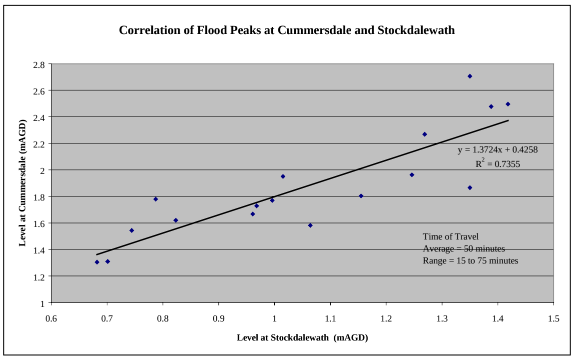
RTM1. EMPIRICAL METHODS: LEVEL-LEVEL CORRELATION

North-West Region: River Caldew

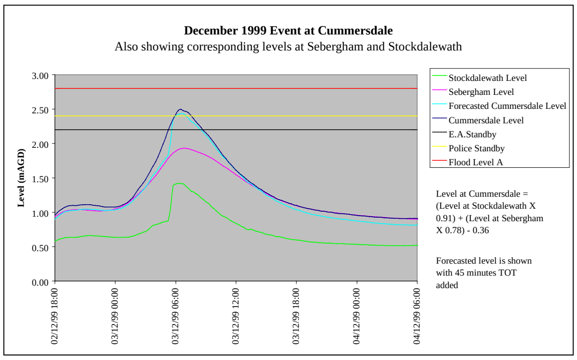
An example of the peak correlation method for forecasting levels is provided by the River Caldew, a (244 km^2) catchment upstream of the Denton Holme flood warning zone at Carlisle.

Observed peak levels at the Stockdalewath and Sebergham gauging stations have been correlated to provide level forecasts at the Cummersdale gauging station, approximately 15 km downstream.



The example event (highest recorded event at Stockdalewith and Cummersdale and third highest recorded event at Sebergham) demonstrates accurate forecasting of peak levels and the recession limb of the hydrograph. The rising limb is poorly forecasted (see ‘Strengths and Weaknesses’.

Forecasting correlations are used at approximately 20 other locations in north-west England. The correlations vary in complexity, most correlating level/flow at an upstream station with level/flow at a downstream station.

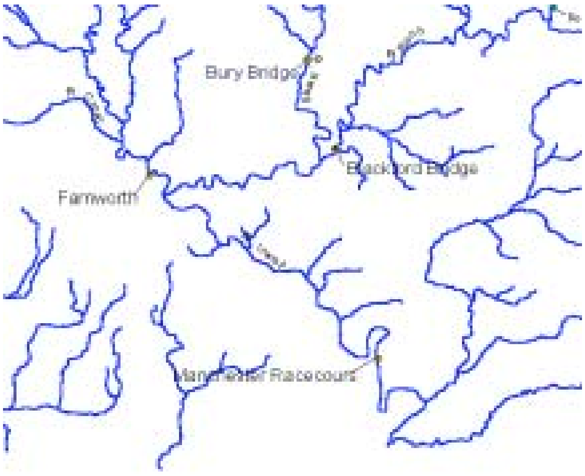


RTM2. EMPIRICAL METHODS: FLOW-FLOW CORRELATION

North-West Region: River Irwell

An example of correlating flow at a downstream gauging station with flows from a number of upstream tributaries is provided by the River Irwell.

The River Irwell drains a catchment of 560 km^2 above Salford, rising in the Forest of Rossendale section of the Pennines north of the towns of Rochdale, Rawtenstall and Bolton. There are two major upstream tributaries, the rivers Roch and Croal.

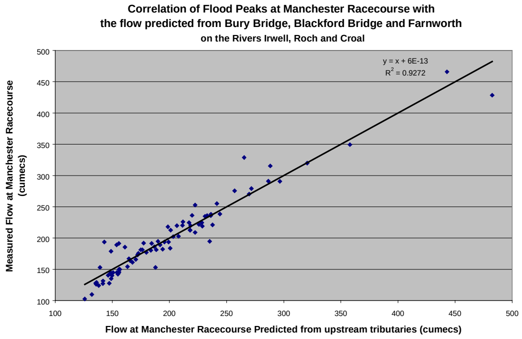


The headwaters of all three rivers drain peat moorland at elevations reaching 480m AOD and all have several small reservoirs impounding the headwaters. The majority of the catchment is heavily urbanised, particularly along the river valleys. The Irwell flows directly into the Manchester Ship Canal at the confluence with the River Medlock, to the south-east of Salford flood risk area.

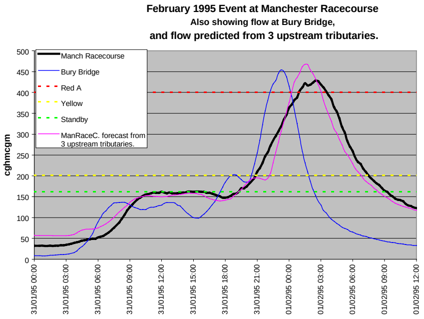
The flow correlation for the main flood warning station for Salford at Manchester Racecourse shown in the following figure is based on flow in three upstream tributaries and takes the following form:

Manchester (cumecs) = (0.383xBury)+(0.492xBlackford)+(1.503xFarnworth)+40.232

The correlation provides approximately 2 hours forecast lead-time.



The example event shown in the following figure is the second highest flood on record at Manchester Racecourse.



Notes:
The forecast hydrograph is shown with TOT of 2 hours already added

Flow at MCR=
0.3831x Bury Bridge
+ 0.4923x Blackford Bridge
+ 1.5029x Farnworth
+ 40.2315

The rating at all upstream stations is suspect.
The hydrograph for Bury Bridge is included to indicate this.

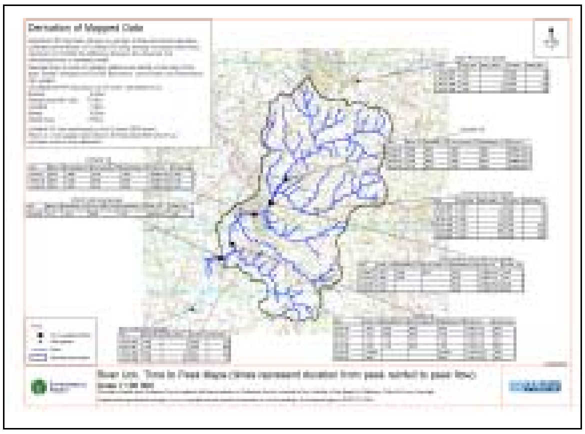
There have been occasions when an upstream station has peaked after Manchester Racecourse. This could indicate that rainfall began in the south of the catchment before progressing northwards to the headwaters.

RTM3. EMPIRICAL METHODS: TIME OF TRAVEL MAPS

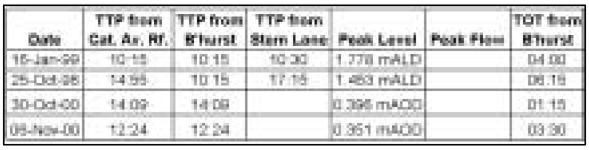
Southern Region: River Uck

Maps showing flood travel times are currently being prepared for all catchments in the Southern Region of the Environment Agency. Time of travel maps will be used by Agency flood warning staff to predict flood peak times where required in the catchment.

For each catchment, two maps will be produced. The first will show the locations of level and rainfall gauging sites, with tables showing a selection of historic events. Average travel times will also be shown, calculated from the analysis of the historic events. The Uck catchment is shown below.



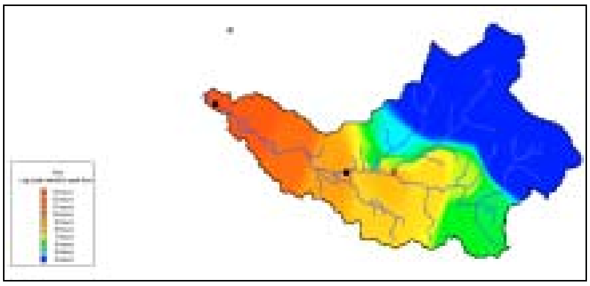
Example time of travel information for a level gauging station are shown in the following table.



Date	TTP from Cat. Av. Rf.	TTP from B'hurst	TTP from Stem Lane	Peak Level	Peak Flow	TOT from B'hurst
15-Jan-99	10:15	10:15	10:30	1.778 mALD		04:00
25-Oct-98	14:55	10:15	17:15	1.463 mALD		06:15
30-Oct-00	14:09	14:09		0.396 mAOD		01:15
06-Nov-00	12:24	12:24		0.351 mAOD		03:30

Travel times shown on the following map are relative to upstream level gauges, and the time of the storm event at rainfall gauging sites. The maps give estimates only, as travel times are dependent on the nature of the particular storm event, and the catchment conditions at the time of the event. As a range of historic storm information is shown on the maps, there is some allowance for interpretation of variability in travel time for different storm events.

The following map produced for each catchment is printed on transparency, and used to overlay the first map. It shows times-to-peak estimated at points across the catchment using standard Flood Estimation Handbook (CEH Wallingford, 2000) procedures and calibrated using the historic data. The time-to-peak values were used to produce a two-dimensional isochrone map of the catchment, which illustrates the time of travel for flood waves through the catchment. An example for the Uck catchment is shown below.



RTM4. EMPIRICAL METHODS: ANTECEDENT PRECIPITATION INDEX

General example from the USA

The Antecedent Precipitation Index (API) model is procedure for approximating the soil moisture condition of a catchment.

It consists of 3 three-variable relations (shown in graphical form on the figure) relating basin recharge as the dependent variable to the antecedent precipitation (API), date (week number), the rainfall amount and the rainfall duration as the independent variables. Basin recharge is defined as the loss due to interception, infiltration and depression storage (i.e. the difference between precipitation and runoff).

The procedure is used widely by River Forecast Centers in the United States to calculate effective rainfall (i.e. precipitation less basin recharge) on a continuous basis (at a six hour time step). Effective rainfall is then routed through a unit hydrograph to determine river flow.

The procedure was first developed by Kohler (1944). It is a robust, simple and computationally undemanding means of determining effective precipitation that requires a very limited number of data inputs (once calibrated the model will operate on just rainfall). However, because of its simplicity it does only provide an approximation of effective rainfall. Since computations are often based on a long time-step (e.g. 6 hours) it provides a particularly poor representation of the impact of high intensity short duration events. As a unit hydrograph model it does only simulates surface runoff and does not directly model baseflow.

A more detailed description of the API model (as applied by the Colorado River Forecast Center can be found at :

http://www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/part2/html/api-slc.htm

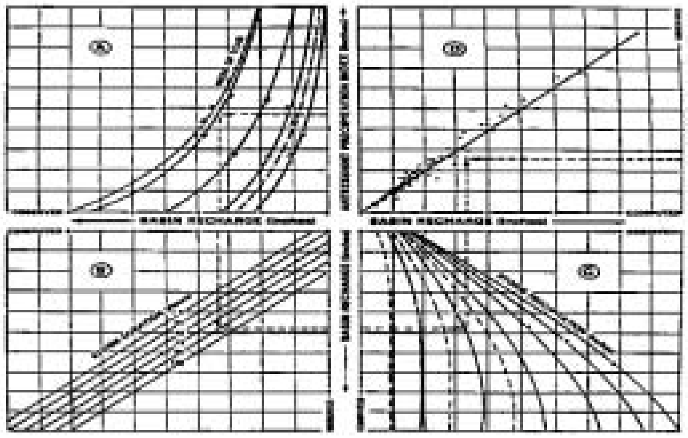


Figure 1. Coaxial relation -- Antecedent Precipitation Index

RTM5. EMPIRICAL METHODS: FLOODWATCH THRESHOLDS

Thames and Midland Regions

In Midland Region a simple soil moisture accounting system is used to support the decision to issue a Floodwatch.

The system is based around an Excel spreadsheet (see table). The table shows the Severn catchment divided into eight units – as shown in the catchment map.

Forecast rainfall for durations between 6 and 24 hours and current SMD are entered into the table. For each unit these forecast rainfalls and the current SMD are compared to Floodwatch criteria developed based on expert interpretation of catchment charateristics. Simple Excel "if" statements (in the Criteria Met? columns of the table) are used to compare forecast rainfall and SMD with the Floodwatch criteria in order to indicate whether a Floodwatch should be issued.

It is important to stress that the Midlands approach is only used to assist decisions to issue Floodwatch. The expertise of the Duty Officer is required to interpret the information presented in the table. The reliability of this model is dependent on the accuracy of the rainfall and SMD data (both of which are lumped to represent large geographical units and are hence prone to inaccuracy). The model is also very crude (it represents runoff as the difference between rainfall and SMD) and hence often fails to adequately represent the runoff process.

The forecasting team in the Midlands Region recognise the limitations of the model and are looking to replace it using output from the rainfall-runoff models in their next generation forecasting system. In the meantime they consider it as a satisfactory stop-gap to meet their Floodwatch forecasting needs.

Area for Floodwatch Assessment		**Next 24 hrs worst case rainfall**				**SMD**	**Flood Watch Criteria SMD**				**Criteria Met? SMD/RAIN**				**Flood Watch Y/N**
		6hr	12 hr	18 hr	24 hr		**<5**	**5 to 20**	**21 to 40**	**>40**	**<5**	**5 to 20**	**21 to 40**	**>40**	
US1	North Powys area including Llanidloes, Newtown, Welshpool and Oswestry	3.8	5.8	8.8	10.8	39.0	20mm in 6 hrs or 25mm in 12 hrs	25mm in 6 hrs or 30mm in 12 hrs	30mm in 6 hrs or 40mm in 12 hrs	30mm in 6 hrs or 45mm in 18 hrs	NO	NO	NO	NO	**NO**
US2	North Shropshire area including Shrewsbury, Telford and Wem	3.0	5.0	8.0	10.0	50.3	24mm iin 6 hrs or 30mm in 12 hrs	28mm in 6 hrs or 35mm in 12 hrs	32mm in 6 hrs or 40mm in 12 hrs	35mm in 6 hrs or 45mm in 18 hrs	NO	NO	NO	NO	**NO**
US3	South Shropshire area including Ludlow, Church Stretton and Bridgnorth	3.0	5.0	8.0	10.	50.8	24mm in 6 hrs or 30mm in 12 hrs	28mm in 6 hrs or 35mm in 12 hrs	32mm in 6 hrs or 40mm in 12 hrs	35mm in 6 hrs or 45mm in 18 hrs	NO	NO	NO	NO	**NO**
US4	The Black Country and North Worcestershire area including Bromsgrove, Kidderminster and Worcester	2.0	4.0	6.0	8.0	50.3	18mm in 6 hrs or 23mm in 12 hrs	20mm in 6 hrs or 25mm in 12 hrs	25mm in 6 hrs or 30mm in 12 hrs	25mm in 6 hrs or 30mm in 12 hrs	NO	NO	NO	NO	**NO**
LS1	Upper Avon Valley including Coventry, Rugby, Warwick and Leamington	2.0	4.0	6.0	8.0	63.1	10mm in 6 hrs or 13mm in 12 hrs	13mm in 6 hrs or 18mm in 12 hrs	18mm in 6 hrs or 23mm in 12 hrs	20mm in 6 hrs or 28mm in 12 hrs	NO	NO	NO	NO	**NO**
LS2	Lower Avon Valley including Stratford, Redditch, Evesham, Shipston and Alcester	2.0	4.0	6.0	8.0	60.3	15mm in 6 hrs or 19mm in 12 hrs	18mm in 6 hrs or 23mm in 12 hrs	23mm in 6 hrs or 28mm in 12 hrs	23mm in 6 hrs or 30mm in 18 hrs	NO	NO	NO	NO	**NO**
LS3	Severn Vale including Cheltenham, Gloucester, Tewkesbury and Forest of Dean	2.0	4.0	6.0	8.0	62.0	12mm in 6 hrs or 16mm in 18 hrs	16mm in 6 hrs or 25mm in 18 hrs	25mm in 12 hrs or 32mm in 24 hrs	35mm in 12 hrs or 40mm in 24 hrs	NO	NO	NO	NO	**NO**
LS4	Severn Estuary including Severn Beach and Gloucester														

Specific Flood Warning Areas within UT3:
TR2 Penk Penkridge to Stafford
TR3 Sow Great Bridgeford to Great Haywood
TR5 Trent Great Haywood to Yoxall
TR6 Trent Yoxall to Drakelow
TR7 Trent Drakelow to Clay Mills
BI1 Blithe Blythe Bridge to Blithfield
BI2 Blithe Blithfield to Nethertown
EG1 Eggington Brook
Eggington Common to Willington
MA1 Marchington Brook
Church Lane to Green Lane
PK1 Pickstall Brook
Stafford Road to Racecourse
RO1 Rolleston Brook
Anslow to Rolleston
SW1 River Swarbourne
Woodmill to Whychnor
Te1 Tean Upper Tean to Uttoxeter
Do3 Dove Rocester to Doveridge
Do4 Dove Doveridge to Marston
Do5 Dove Marston to Clay Mills

UT4:STOKE & ASHBOURNE including NEWCASTLE-UNDER-LYME, LEEK & STONE
Specific Flood Warning Areas within UT4:
LY1 Lyme Brook Newcastle to Hanford
TR1 Trent Stoke to Darlaston
TR4 Trent Darlaston to Great Haywood
Do1 Dove Izaak Walton to Rocester
Do2 Churnet Leek to Rocester

DE5 Derwent Ambergate to Spondon
DE6 Derwent Borrowash to Church Wilne
ER1 Erewash Pinxton to Long Eaton
TR8 Trent Burton to Castle Donington
TR9 Trent Castle Donington to Long Eaton

UPPER SEVERN AREA

US1:NORTH EAST POWYS including LLANIDLOES, NEWTOWN, WELSHPOOL & THE OSWESTRY AREA OF SHROPSHIRE
Specific Flood Warning Areas within US1:
S1 Severn Llanidloes to Glandulais
S2 Severn Glandulais to Caerhowel
S3 Severn Caerhowel to Trewern
S4 Severn Pool Quay to Crew Green
V1 Vyrnwy Newbridge to Llansantffraid
V2 Vyrnwy Llansantffraid to Shrawardine

US2:NORTH SHROPSHIRE including SHREWSBURY, MARKET DRAYTON & TELFORD
Specific Flood Warning Areas within US2:
S5M Severn Shrawardine to Shelton
S5S Severn Shelton to Monkmoor
S6C Severn Monkmoor to Buildwas
S6I Severn Buildwas to Coalport

US3:SOUTH SHROPSHIRE including KNIGHTON TENBURY, CHURCH STRETTON & BRIDGNORTH
Specific Flood Warning Areas within US3:
S7 Severn Coalport to Highley
T1 Teme Ludlow to Bransford Bridge

US4:THE BLACK COUNTRY & NORTH WORCESTERSHIRE including WOLVERHAMPTON, BROMSGROVE, KIDDERMINSTER & WORCESTER
Specific Flood Warning Areas within US4:
T2 Teme Bransford Bridge to Powick
S8 Severn Upper Arley to Bewdley
S9 Severn Bewdley to Powick
K1 Stour Kidderminster

A simpler system, based purely on rainfall thresholds is used in the West Area of Thames Region (as illustrated in the following table). Again, the expert knowledge of a Duty Officer is required to interpret the output of this system.

Rainfall rates	**>15mm in 12 hrs** **>25mm in 24 hrs**	**>20mm in 12 hrs** **>30mm in 24 hrs**	**>25mm in 12 hrs** **>40mm in 24 hrs**	**>40mm in 12 hrs** **>60mm in 24 hrs**
Catchments	Ampney Brook Cherwell Lower Kennet (Enbourn) Ock Sulham Brook Ray (Oxon) Thame Windrush	Cole Evenlode Pang Upper Thames	Churn Coln Upper Kennet Leach Ray (Wilts)	Wye

RTM6. EMPIRICAL METHODS: THRESHOLD EXCEEDANCE TABLES

Anglian Region: Great Ouse

A HEC-HMS model of the Great Ouse catchment upstream of Earith developed by Edinburgh University (Edinburgh University, 19xx) has been used to derive look-up tables for five key flood risk zones in the upper catchment. The look-up tables provide forecasts for a range of storm durations and depths, for:

T_f	the duration in hours between the end of a rainfall event to the exceedence of either the Flood Warning or Severe Flood Warning threshold
Q_p	the peak flow
T_p	the duration in hours between the end of a rainfall event to the peak flow

An example look-up table for the gauging station at Brackley, for soil moisture deficits in the range 0 –10 mm is shown in the following table.

SMD = 0-10 mm

			Storm Depth (mm)					
			20	30	40	60	80	100
Storm Duration	6 hours	T_f	N/A	N/A	6	3.5	2	1
		Q_p	4	7.6	11.8	21.8	33	45
		T_p	9	9	9	9	9	9
	12 Hours	T_f	N/A	N/A	4	1	-1	-1
		Q_p	3.9	7.3	11.4	21	32	43
		T_p	7	7	7	7	7	7
	24 hours	T_f	N/A	N/A	2	-4	-7	-8
		Q_p	3.4	6.4	10.1	18.5	28	38.1
		T_p	2	2	2	2	2	2

Key

6.4	Below Flood Warning Threshold
10.1	Flood Warning
18.5	Severe Flood Warning

T_f	Time (hrs) to reach threshold
Q_p	Peak Flow (cumecs
T_p	Time (hrs) to peak flow

A forecaster would use a look-up table by:

1. Selecting the table for the appropriate gauging station and catchment soil moisture deficit.

2. Reading off the forecast from the selected table for the appropriate storm duration and depth (e.g. the peak flow (Q_p) for a storm of 12 hours and 60 mm in the catchment upstream of Brackley gauging station is forecast to be 21 cumecs.

HEC-HMS offers a wide range of approaches to flood run-off simulation. The fundamental components of the model are

- A rainfall loss model for runoff computation

- A unit hydrograph model to route rainfall excess to catchment outflow

- A channel routing model to connect the sub catchments and route hydrographs through the river network

For the Great Ouse model an SCS curve number approach was used for the rainfall loss model (calibrated by the selection of an SCS infiltration curve (CN) and an initial loss (S)). The rainfall excess from this model was routed to the catchment outflow using a SCS unit hydrograph (defined, like the FEH unit hydrograph, as a function of LAG. An eight point Muskingum-Cunge routing method was tried (unsuccessfully) to route flows through the lower reaches of the model. This straightforward approach was deliberately chosen to allow a simple yet robust model to be set up relatively quickly.

The National Weather Centre in the United States uses variations on this approach widely in flood forecasting models. The method has proved effective for simulating single events similar to those against which it was calibrated. However, it initially proved less successful at simulating “second flood events” (i.e. those generated by rainfall on already saturated ground). In order to overcome this problem, an additional series of calibrations have been undertaken against observed flood events generated by saturated catchments and an additional series of “second flood event” look-up tables have been produced.

RTM7. BLACKBOX MODELS: UNIT HYDROGRAPHS

Red River of the North, North Dakota, USA

A winter of numerous heavy snowstorms and the ensuing spring snowmelt caused a major flood on the Red River of the North along the Minnesota - North Dakota border in the United States. At Fargo, North Dakota, flood stage exceeded the 100 year threshold, whilst at Grand Forkes (North Dakota's third largest city) and East Grand Forkes, 60,000 residents were evacuated. In total 11 people died in North Dakota and Minnesota as a result of the flood and the flood damage was estimated to be $1-2 billion.

Forecasts provided by the North Central River Forecast Centre (NCRFC) significantly under-predicted the magnitude of the event. A review of the forecasting techniques used revealed important lessons for flood forecasting in general and also highlighted some key limitations of hydrological routing models and the appropriate application of updating routines.

The forecasting procedures used at the time of the flood are summarised in the following table and comprise:

- a unit hydrograph approach to simulate runoff
- TATUM (a storage routing procedure) to simulate channel and flood plain routing
- STAGE-Q to convert modelled flow to stage and vice-versa (using a single line stage discharge relationship
- ADJUST-Q to correct modelled discharges with observed discharge

This approach was found to have two key weaknesses.

- the model's reliance on extended single line stage-discharge relationships. Like all forecast models it required accurate observed flow data (most often derived through ratings) with which to update simulated flows. Since the key output of any forecasting model is stage, it also required reliable stage discharge relationships to convert simulated discharge (the output from the TATUM routing procedure) to a forecast flood level.

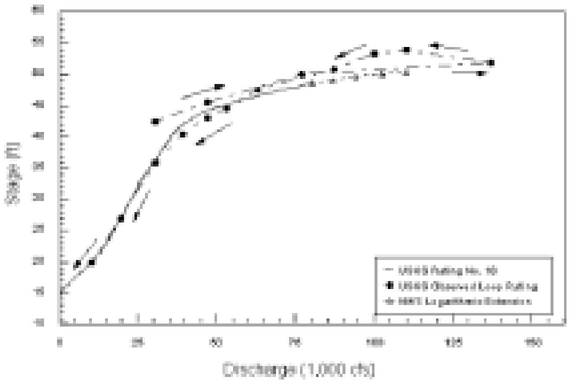
  During the 1997 event forecasters at the NCRFC used a logarithmic method to extend the East Grand Forkes gauging station rating (see following figure). This method significantly underestimated flood levels in the flood risk zones of Grand Forkes and East Forkes. This type of rating extension proved inappropriate because it failed to account for the variable relationship between stage and discharge caused by backwatering from bridges, debris and runoff from downstream tributaries. The actual looped rating (measured during the event) is also shown in the figure.

- the inability of the simple hydrological routing procedure to simulate complex flood plain processes. The Red River (described by one National Weather Service official as a thin scratch down a flat board) drains an area of low gradient criss-crossed by railway and road embankments. The TATUM routing procedure failed to simulate the

- significant back-watering and storage processes induced by these features.

Operation	Purpose
SNOW-17	Accounts for snow accumulation and melt
MKC-API	Determines the runoff from the basin
UNIT-HG	Converts runoff from the basin into stream channel discharge at the forecast point
BASEFLOW	Determines the baseflow contribution to the hydrograph
ADD/SUB	Adds together the various flows coming into the forecast point (including the local runoff from the UNIT-HG)
TATUM	Storage routing procedure which routes water coming from upstream to the forecast point
ADD/SUB	Adds the baseflow into the routed flow
STAGE-Q	Converts observed stage values to discharge using the rating curve
ADJUST-Q	Updates the simulated discharge values using observed values
STAGE-Q	Converts simulated discharge to simulated stage using the rating curve
PLOT-TUL	Displays selected results of the operations including the outflow hydrograph

Since the 1997 event the National Weather Service (the body responsible for the NCRFC) have implemented a one dimensional unsteady flow forecasting model FLDWAV for the Red River. This model will improve their flood forecasting capabilities for the catchment by more reliably simulating the looped stage discharge relationships at key gauges caused by backwatering and provided an improved representation of the complex floodplain flow processes operating during flood conditions.



The lessons learned by the NCRFC following the April 1997 event on the Red River have significant relevance to flood forecasting in the UK. In summary they are:

- The inappropriateness of simple hydrological routing methods for simulating channel and floodplain processes in flat and / or hydraulically complex river systems.

- The need to be able to quantify errors associated with stage discharge relationships when deriving flood level from the flow output of a simple hydrological routing model

- Cautious use of observed flows in updating. Only reliable observed flows should be used to update forecasts.

An understanding of the features and characteristics of the catchment being modelled. NCRFC may have been able to improve the forecasts for Grand Forkes if they had been aware of the bridges causing backwatering at the East Grand Forkes Gauge.

RTM8. BLACKBOX MODELS: TRANSFER-FUNCTION (PRTF)

North-West Region: River Greta

A PRTF model has recently been developed to forecast flows for the River Greta at Low Briery – a river gauging station upstream of Keswick, a town with a long history of flooding.

When operational, forecast flows to Low Briery will be converted into levels and a level-level correlation between Low Briery and two logger sites located downstream in Keswick. The level correlations will extend forecast lead-time by between 15 and 45 minutes providing an overall forecast lead times of up to two hours.

Rainfall depths from a number of rain gauges are used to provide estimates of catchment rainfall at hourly intervals. The PRTF model has been calibrated using a calibration sequence comprising of eight recent flood events and has three rainfall parameters, three flow parameters, and a pure time delay of one hour.

The form of the calibrated model is:

$$Q_t = 2.319Q_{t-1} - 1.793Q_{t-2} + 0.462Q_{t-3}$$
$$- 0.160R_{t-2} + 1.182R_{t-3} - 0.737R_{t-4}$$

It is interesting to note that in this case, the inclusion of a one-hour time delay provides the ability to forecast flow for up to two hours ahead without the use of quantitative precipitation forecasts.

RTM9. BLACKBOX MODELS: TRANSFER-FUNCTION (PRTF)

South West Region: River Tone

A further example of a PRTF model is for the River Tone at Bishops Hull near Taunton (South-West Region).

A feature of the catchment is the significant inter-event variability in hydrograph shape. To address this, a two-phase calibration approach has been developed. In the first phase, model parameters are estimated for a single, significant flood event. The form of the calibrated model is shown below:

$$Q_t = 2298Q_{t-1} - 1.760Q_{t-2} + 0.449Q_{t-3}$$
$$- 0.124R_{t-2} + 0.163R_{t-3} - 0.057R_{t-4} + 0.375R_{t-5}$$

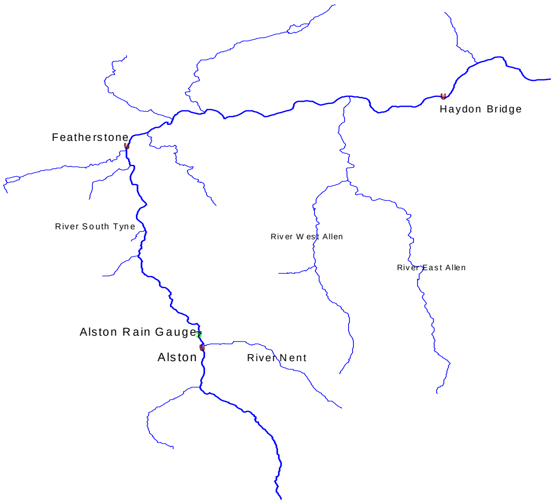
In the second phase, events grouped together according to the catchment wetness index (CWI) are used to adjust the volume, shape and timing parameters. This approach provides a ‘suite’ of five models for the catchment as shown in the following table. The model is run on an event basis.

	CWI	Volume	Volume	Shape	Time
‘Summer’	<50	15	-70	0	0
‘Summer’	50-100	25	-50	0	0
‘Spring/Autumn’	100-125	35	-30	0	0-1
‘Winter’	125-140	43	-15	0	0-1
‘Winter (saturated)’	>140	100	0	0	0

RTM10. BLACKBOX MODELS: ARTIFICIAL NEURAL NETWORK

North East Region: South River Tyne

An investigation into the application of artificial neural networks for hydrological modelling of the South-Tyne catchment in north-east England was recently concluded. South Tyne to Haydon Bridge has a catchment area of 751.1 km^2, a mean annual rainfall of 1181 mm, a mean annual runoff of 769 mm, and a mean annual flood of 365.1 m^3 s^{-1}. The rivers Nent and East and West Allens are important, ungauged lateral inflows. There is an approximate lag time of 4 h between the tipping-bucket rain gauge at Alston and the river gauging station at Haydon Bridge.



The catchment is currently modelled within the regional flood forecasting system using a conceptual rainfall-runoff (PDM) and kinematic wave routing models. The neural network approach was investigated as an alternative approach.

A neural network utilises a pattern matching process to map input variables (e.g. rainfall) to the forecast output (e.g. river stage). In the trial, stage data for the river gauging stations at Alston, Featherstone and Haydon Bridge and rainfall data from the Alston rain gauge provided inputs to the neural network model. The net attempts to match these with the pattern at the output station. Since the neural nets operate directly upon stage data, rating equations are not required. The neural network model does not possess a model updating procedure.

The neural net is not a routing model. To forecast at station *z* on the basis of inputs at stations *x*, *y* and *z* it looks upstream for data for the same hydrological event. If a flood wave passes point *z* at 12.00, it passed point *y* earlier in the day at say 9.00 and station *x* at say 06.00. The network uses a 'travel time' identified by a trial and error process by the model developer. The net uses the travel times to look back in the record and pick up the data for the hydrograph passing stations earlier in the sequence. The travel times were: 0 h (Alston rainfall to Alston gauging station), 1 h (Alston to Featherstone), and 2 h (Featherstone to Haydon Bridge).

The structure of a neural network model defines its forecast time periods. Thus a 'suite' of neural networks are developed, one being used for each forecast lead-time. Thus, if forecasts are required for 1, 2 and 4 hours ahead – three different neural network models have to be calibrated ('trained').

Models are trained using a conventional objective function – i.e. minimise sum of squared errors

The model was assessed in terms of its ability to simulate a continuous river stage record (using the Nash and Sutcliffe efficiency measure) with additional consideration being given to the forecasts of flood peak magnitudes and timings over different forecast horizons (using the mean of absolute errors).

The neural networks provided good simulations of the calibration data. However, forecasting performance, assessed using independent verification events was significantly poorer with the larger events being significantly underestimated. This is a fundamental limitation of using a data-based black-box modelling approach to event data that is extends beyond the envelope of the calibration data. Further investigations highlighted significant sensitivity of forecasting performance to the events used for training relative to the forecast events: the use of separate neural network models for different magnitude flows. Error prediction could also improve model performance, although there are problems associated with this.

In its current form, the neural network approach evaluated in this study would appear to be limited to providing forecasts of small to moderate sized floods for the River South Tyne at Haydon Bridge.

The above text is reproduced with the kind permission of Dr David Cameron (EA North-East, Northumbria Area). Further information of the North-East neural network trial is provided in Cameron *et al* (2001) – see main report references.

RTM11. CONCEPTUAL MODELS: MIKE 11 RAINFALL RUNOFF

General example

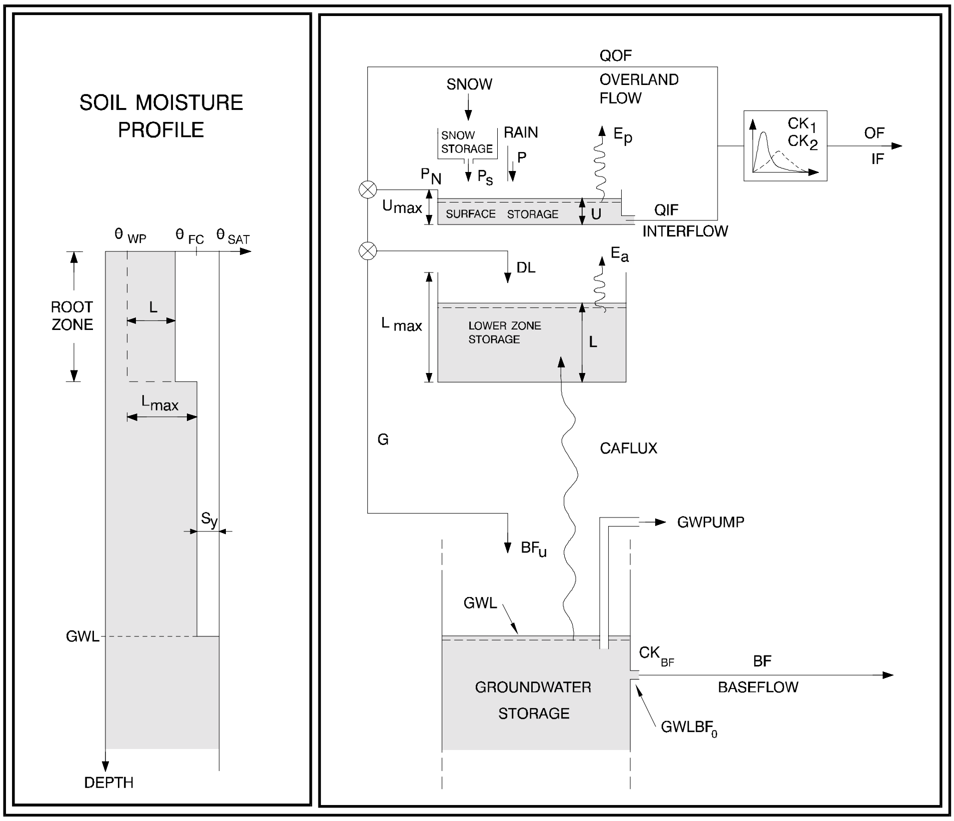
An example of this class of model is MIKE11-RR (formerly known as MIKE-NAM).

MIKE11-RR is a classical lumped, conceptual hydrological rainfall-runoff model that uses physical and semi-empirical formulations to describe:

- Snow storage
- Surface storage
- Lower (soil) zone storage
- Groundwater storage

Conceptual models such as MIKE11-RR can be run for isolated events or continuously. The advantage of the latter is that reservoir stores are constantly updated and therefore always accurately represent current conditions. If these models are not updated a key source of error can be the initial store conditions selected by the user.

A schematic view of the structure of MIKE11-RR is provided in the figure. As with most conceptual models MIKE11-RR includes a total a large number of parameters (17 in total). However, in most cases a satisfactory calibration can be obtained by adjusting only about 10 of these.



RTM12. CONCEPTUAL MODELS: SNOWMELT MODELS

North-East, Anglian and Midlands Regions

The North-East, Anglian and Midlands Regions flood forecasting systems incorporate explicit monitoring and modelling of snowmelt.

Snowmelt can be a significant contributor to winter flooding. In January 1982, snowmelt contributed to the flooding of 800 properties around Selby and York, in Nottingham at Trent Bridge 10 of the 35 highest flood flows were associated with melting snow and melt rates as large as 60mm per day from a small catchment in the Pennines have been quoted. It has been noted that during periods of snowmelt, the use of a snowmelt model component improves upon the accuracy of flow forecasts obtained using a rainfall model alone.

The most detailed snowmelt models use a full set of energy balance equations to describe melt, including net radiation, temperature, wind speed and humidity. However, the data inputs required are rarely available, especially in real time, and therefore more empirical methods are generally used. The most common is the temperature index method, which requires only measurements of air temperature

The North East and Anglian Regions both use the PACK model. The model has four basic components, which are listed below.

- An input transformation corrects precipitation measurements (for example for gauge loss or altitude and aspect effects) and then a temperature threshold is used to discriminate between rain and snow.
- A melt equation uses a simple temperature excess to govern the rate of melt.
- The snowpack is divided into ‘wet’ and ‘dry’ stores. New snow falling onto the pack is added to the dry store, and melt water is taken away. The wet store receives melt from the dry store, and also receives water as rainfall. The release of water as drainage from the wet pack occurs at a rate proportional to the wet pack storage.
- An areal depletion curve accounts for the fact that shallow snowpacks may only occupy a fraction of the catchment. The fraction of snow cover varies as a function of the total water equivalent of the pack.

The PACK model has nine parameters. Snow cores taken in the field at selected points give details of the depth and water equivalent of the snowpack and provide a means of estimating these parameters. In the North East Region, a snow observer records the depth and average weight of snow by taking snow cores at selected sites, When the depth of snow exceeds 100mm the data is phoned in to the Regional Call Centre (RCC) and observations are manually added onto the RFFS. There is a snow pillow at Cow Green in the North East Region, however it has been noted that the use of hourly snow pillow data does not easily improve on flow modelling results obtained using daily snow core observations.

In the Midlands Region, the rainfall-runoff model used for flood forecasting includes a simple snowmelt component. The snow input is estimated from heated rain gauges and air temperature measurements. Changes of snow density, snowmelt and routing of melt through the snowpack are computed by the model at an hourly time intervals, and occasional manual state updating of depths and densities of snow are made. A set of four relations controls the detailed operation of the model, and these are summarised below.

- The snowpack depth is decreased by a proportion during the model interval, and the compaction coefficient is temperature dependent.

- Rainfall recorded is assumed to have fallen as snow if the air temperature is below a critical value.

- The density of fresh snow is temperature dependent.

- The potential snowmelt is calculated using a simple temperature index equation.

The snow depth and water equivalent are updated when precipitation falls and the snowpack density is calculated. When snowmelt occurs, it is absorbed by the pack until the pack density exceeds a critical value, then melt is released and input into the rainfall-runoff model.

RTM13. ROUTING MODELS: STORAGE ROUTING (DODO)

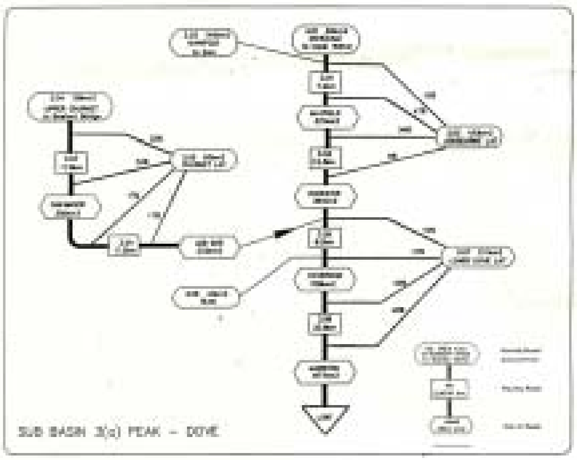
Midlands Region

The Dobson-Douglas (DoDo) routing model is a hydrological routing model used in the Midlands Flow Forecasting System.

The model is based on the Muskingum storage function relating volume of storage in a reach with reach inflow and outflow. Reach input is lagged, with the lag decreasing a power function of each inflow.

In order to distinguish the very different flow characteristics of the flood plain, the model contains a second Muskingum storage to represent out of bank flow (with a further store to account for initial contribution to static floodplain storage). On the recession water in static storage drains out of the reach, initially slowly but then freely below a critical return bankful storage as a power function of the volume of water in static floodplain storage.

Lateral inflows to the reach are divided equally between the reach inflow and the reach outflow; a downstream input can also be added to the routed outflow to give the final reach outflow. The DoDo model has a total of 12 parameters, six representing in channel flow and six for out of channel flow.



The DoDo model is applied most successfully to river reaches with relatively steep gradients and limited floodplain, such as the Severn between Ironbridge and Bewdley, where backwatering and complex floodplain processes are not a significant influence on flow. The model is less successful in locations where backwatering and floodplain process strongly influence flow, such as the confluences of the lower

Severn or the Severn downstream of Gloucester.

RTM14. ROUTING MODELS: HYDRODYNAMIC (ISIS)

North West Region: River Eden

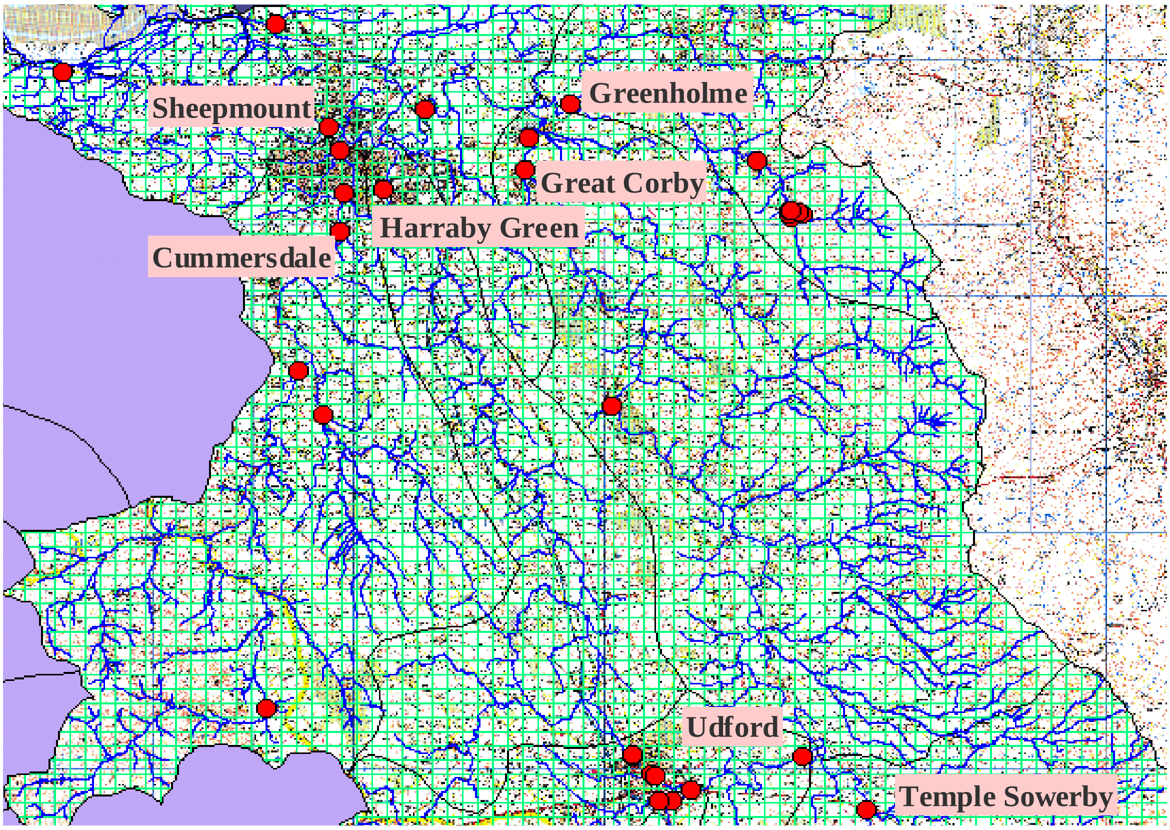
The North-West Region has recently supported the development of a real-time 1-D HD model for the River Eden in Cumbria.

The river Eden catchment and its tributaries cover an area of 2404 km^2. The main tributaries include the Rivers Caldew, Petteril, Eamont, Lowther and Irthing. The Lowther and Eamont join the Eden east of Penrith. The Irthing joins the Eden approximately 9 km upstream of Carlisle. Two major tributaries, the Caldew and Petteril, join within the Carlisle City boundary. There is a limited floodplain on both these rivers and the Caldew passes mainly through the urban areas of Carlisle.

The rainfall over the catchment varies considerably. The average annual rainfall is approximately 3800 mm to the south of Haweswater, and 760 mm to the south of Carlisle.

The catchment is predominantly rural and undeveloped with the exception of three main towns, Carlisle, Penrith and Appleby.

The highest points in the catchment are Skiddaw at 931m AOD at the head of the River Caldew and Helvellyn at 950m AOD, standing above Ullswater - the source of the River Eamont. The other large lake is Haweswater, which feeds Haweswater Beck and then continues to the River Lowther.



The HD model is part of a real-time river model whereby river flows from two gauging stations located upstream of the confluence of the rivers Eamont and Eden (at Udford and Temple Sowerby) are hydrologically routed using Muskingum VPMC to the upstream boundary of the HD model at Warwick Bridge upstream of the flood risk area of Carlisle.

From this point on, the model is fully HD to downstream of Carlisle. In its current form, the model provides approximately 5-6 hours forecast lead-time, although this could be extended considerably by the incorporation of rainfall-runoff models above the Eden and Eamont gauging stations.

RTM15. ROUTING MODELS: HYDRODYNAMIC (MIKE11)

Anglian Region: Rivers Welland and Glen

A flood forecasting model of the Welland and Glen catchment has been developed by WS Atkins in conjunction with DHI Water and Environment as a pilot for the Anglian Flow Forecast and Modelling System.

The models incorporate the MIKE 11 standard state updating routine. Updating places a substantial additional demand on computational time because model forecast runs have to be iterated in order to stabilise the model: thus, it proved desirable to limit the number of updating points in the model to between five and twenty. During the calibration process the number of model iterations required was set to two.

Updating points for the model were selected using the criteria listed in the following table.

Criteria	Comment
Sites for which accurate data area available	Updating using unreliable data will degrade model performance. When updating on discharge it is essential to use a site with a reliable stage -discharge relationship for the full range of flows. When updating against level it is essential for the channel and floodplain topography in the vicinity site to be accurately represented (to ensure that the model's computation of correction flow is reliable).
Sites that measure a significant proportion of the total flow of the catchment	Concentrating updating on monitoring points that record runoff from a large proportion of the catchment ensures that the benefit of updating is maximised.
Sites where reliable forecasts are particularly important for operational purposes should be favoured	Updating at operationally important sites (e.g. upstream of major flood risk zones) will optimise the performance of the model in key locations

The final selection of updating points is shown in the following table. Note that only a very limited number of sites (i.e. those with good high flow ratings) could be used for flow updating and how Market Harborough, a key high and low flow site - is updated on both flow and level.

Because of the variable quality of flow and level data in the catchment, the updating switch (a function of the Anglian Flow Forecasting and Modelling System) that allows updating to be applied only to a limited flow range) was used extensively.

Site Name	Flow / Level	High Range	Low Range
Jordan	Flow	☑	☑
Ashley[1]	Flow	☐	☑
Market Harborough	Level	☑	☐
Market Harborough	Flow	☐	☑
Medbourne	Flow	☐	☑
Barrowden	Flow	☐	☑
Belmesthorpe	Flow	☐	☑
Fosters Bridge	Flow	☑	☐
Burton Coggles	Flow	☐	☑
Irnham	Flow	☐	☑
Kates Bridge	Flow	☑	☑
Lolham Cut	Flow	☐	☑
West Deeping Cut	Flow	☐	☑
Tallington	Flow	☑	☐
Bourne Eau PS (Glen level)	Level	☑	☑
West Deeping Cut	Flow	☐	☑

The particular lessons learned during the calibration of the Welland and Glen model were:

- The quality of both flow and topographic data provided the over-riding control on the success of updating. Although there is an extensive network of flow and level gauges in the catchment only a small number produced sufficiently reliable data to warrant their use for updating.

- Updating upstream of structures operated by automatic control rules often proved ineffective since the updating function and the gate operation rules often worked to cancel each other out.

- The model was calibrated to forecast both high and low flows. This sometimes caused a conflict in parameter selection (particularly the time constant that determines the rate of decay of the correcting discharge during the forecast period). As a general rule, a short decay period is required for high flows whilst a much longer one is needed for low flows. During calibration a priority was placed on high flow performance, at the expense of the low flow performance.