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Review of Transfer Function Modelling for Fluvial Flood Forecasting

R&D Technical Report W5C-013/6/TR

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Review of Transfer Function Modelling for Fluvial Flood Forecasting

R&D Technical Report W5C-013/6/TR

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EXECUTIVE SUMMARY

Transfer Function models aim to estimate river flows based on current and previous observations of rainfall, and previous values of flow, and are normally data-based, in the sense that both the values of the parameters and the forecast values are derived solely from the information content of the measured data.

Within the Environment Agency, Transfer Function rainfall runoff models are accepted as a valid approach to flood forecasting which has been used in the UK for more than twenty years, although against a background where (i) recent research developments have yet to find their way into Agency use and (ii) there are some known pitfalls in implementation of this type of model.

The present project was therefore promoted by the National Flood Forecasting Group (NFFG) as an extension to previous phases of this research programme (Project W5C-013/6/TR) to provide further clarification on the use of Transfer Function models for flood forecasting applications within the Agency. The main objectives of the project were to:

- Review the state of the art in Transfer Function modelling for fluvial flood forecasting;
- Review existing Environment Agency use of Transfer Function models for fluvial flood forecasting;
- Identify best current practice by Agency practitioners in South West, North Western, Anglian and Southern Regions;
- Provide guidance on the development (calibration and validation) of Transfer Function models; and
- Provide recommendations for future research work.

The scope of work also included consultations with key researchers in the area of Transfer Function modelling, although excluded discussion of specific ‘brands’ of model from software vendors.

This report provides the main output from the project and considers a range of topics including current knowledge concerning model calibration and validation; modelling assumptions; updating techniques; uncertainty; and sensitivity to different model inputs. Best practice approaches are also reported where these could be identified, together with recommendations for future research and operational improvements in the way that Transfer Function models are used within the Environment Agency.

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GLOSSARY OF TERMS

Term	Abbreviation	Definition
Akaike Information Criterion	AIC	A measure of fit used in some automated optimisation procedures
	ARMA	Autoregressive moving average model
Data Based Mechanistic Model	DBM	A type of Non Linear Transfer Function model developed by Lancaster University
Flood Estimation Handbook	FEH	The UK's national approach to design flood estimation
	HYRAD	A radar processing and display system introduced across the Agency in 2002
	IHACRES	Type of parallel pathway model developed at the Centre for Ecology and Hydrology
Instrumental Variable	IV	An approach to model optimisation (also RIV and SRIV)
Multiple Input Single Output	MISO	A Transfer Function model with multiple input time series
National Flood Forecasting System	NFFS	The Agency's new national flood forecasting system environment
National Flood Forecasting Modelling Strategy	NFFMS	The strategy underpinning the NFFS
	NFFG	National Flood Forecasting Group
Physically Realisable Transfer Function	PRTF	A type of Linear Transfer Function model developed by the University of Bristol
Refined Instrumental Variable	RIV	A form of parameter estimation procedure developed from the IV approach
Recursive Least Squares	RLS	An approach to model optimisation
Single Input Single Output	SISO	A Transfer Function model with a single input time series
Transfer Function	TF	
Timeliness		A measure of the lead time of warnings
	TVP	Time Varying Parameters
Young Information Criterion	YIC	A more sophisticated version of the AIC (see above)

1 INTRODUCTION

1.1 Background

1.1.1 General Context

Within the Environment Agency, approaches to the selection of flood forecasting models have recently been transformed into a national guideline document on “Real Time Modelling” (R&D project W5C-013/6/TR; Environment Agency, 2002b). An inter-comparison study of rainfall runoff modelling approaches (R&D Technical Report W242; Environment Agency, 2000) was also completed in 2000. These projects confirmed Transfer Function rainfall runoff models as a valid approach to flood forecasting, although against a background where (i) recent research developments have yet to find their way into Agency use and (ii) there are some known pitfalls in implementation of this type of model. The inter-comparison study also showed that:

- For all model types studied on that project, “the [modelling] results are complex and, predictably, no one model has been found to be best for all types of catchment and assessment criteria.” (Page 159, Section 6.3)
- The two types of Transfer Function which were evaluated performed poorly (Page 159), although the report (Page 150) clearly stated that these formulations did not represent those most commonly used within the Environment Agency.

Following publication of these results, although consideration was given to commissioning further inter-comparison studies, there is presently a view within the Agency that such studies often lead to inconclusive findings.

Instead, there is a preference to promote a modelling/forecasting philosophy referred to as “horses for courses” (see Khatibi *et al*, 2003) which recognises that - for any given physical situation - there is no perfect model and that one modelling technique may perform better than other. The modelling investment is then appropriate to the level of flood risk, and the type and sophistication of model is appropriate for the modelling situation (e.g. catchment characteristics). Integral to this approach is the notion that performance monitoring and operational experience are essential to drive future improvements, and these concepts have been incorporated both into the national guidelines and in the present study.

Given these considerations, the present project was therefore promoted by the National Flood Forecasting Group (NFFG) as an extension to the “Real Time Modelling” guidelines project to provide further clarification on the use of Transfer Function models for flood forecasting applications within the Agency. Some key objectives were to review the use of Transfer Functions in the Agency and to offer guidance to practitioners on calibration and validation procedures, the impact of assumptions, good practise in updating and self-correcting procedures, and methods for quantifying uncertainty.

1.1.2 Role of Transfer Function Models in the Agency

Whilst performance targets can sometimes be met by simple trigger based approaches based upon telemetered river level observations, in many situations the required accuracy and lead time of warning can only be obtained through the use of real time forecasting models.

This is particularly the case on fast response catchments, where rivers may respond rapidly to rainfall and warnings cannot be issued sufficiently early on the basis of river level observations alone. In this situation, the best chance of providing accurate forecasts with a sufficient lead time at a given site often lies in the real time operation of rainfall runoff models, such as Transfer Function models. These models can also be incorporated into more complex integrated catchment models to extend the forecast lead times to Flood Warning Areas further down the catchment; for example, Major Incident Plan locations at major towns and cities.

Minimum Flood Warning Lead Times

The present Customer Charter commitment for "Timeliness" to meet the requirements of the population at risk from flooding is expressed in terms of a lead time of 2 hours, although most Regions aim to offer warnings with a lead time considerably more than this when technically possible, or required for operational reasons (for example, for the operation of control structures and temporary/demountable flood defences). Under the definition of "Service Effectiveness", a recently issued (2003) Agency Management System Work Instruction on flood warning performance measures also highlights that "*the amount of time allowed to prepare for a flood will increase people's readiness up to a certain point. If the length of time since the warning was issued and the onset of flooding is too long, it could lead to people believing that the warning was a false warning and start reinistating preparations* ". Damage Avoidance studies also suggest that that the maximum financial benefits are typically achieved with warnings 4 hours ahead or more (although with little additional financial advantage for warnings much beyond 6-8 hours ahead). A minimum warning time of 4 hours or more may also be required for Major Incident Plans (e.g. potential overtopping of flood defences) whilst there may also be some catchments (e.g. fast response catchments, such as small urban catchments in thunderstorms) where it is not possible to meet the two hour target with current technology (yet even a shorter warning time is of use).

The "Real Time Modelling" guidelines (Environment Agency, 2002b) placed Transfer Function models in the category of Blackbox model, and noted that they are used operationally in South West, North West, Anglian and Southern Regions at present (other types of Blackbox model include the unit hydrograph approach, and research techniques such as neural networks and genetic algorithms which are not used operationally at present).

1.2 Scope of Study

Transfer Function models aim to estimate river flows based on current and previous observations of rainfall, and previous values of flow, and are normally data-based, in the sense that both the values of the parameters and the forecast values are derived solely from the information content of the measured data.

Although this category of model has been used operationally in the UK for more than 20 years, it has been noted within the Agency that both the application of these models and performance evaluation seems to vary from Region to Region, and is often *ad hoc*, in the sense that no nationally consistent approach is followed. Thus this study was commissioned as an extension to the project which led to the "Real Time Modelling" guidelines, and with the following main objectives:

- Review the state of the art in Transfer Function modelling for fluvial flood forecasting;
- Review existing Environment Agency use of Transfer Function models for fluvial flood forecasting;
- Identify best current practice by Agency practitioners in South West, North Western, Anglian and Southern Regions;
- Provide guidance on the development (calibration and validation) of Transfer Function models; and
- Provide recommendations for future research work.

The scope of work also included consultations with key researchers in the area of Transfer Function modelling, although excludes discussion of specific 'brands' of model from software vendors.

This report provides the main output from the project and considers a range of topics including current knowledge concerning model calibration and validation; modelling assumptions; updating techniques; uncertainty; and sensitivity to different model inputs. Best practice approaches are also reported where these could be identified, together with recommendations for future research.

As the report shows, there are new developments in flood forecasting based on Transfer Function models not yet taken up in the Agency. Based on their low cost, their applications in the Agency are expected to increase. Although this extended project was not required to produce a guideline document for the usage of Transfer Function models, the report is sufficiently comprehensive that the compilation of guidelines in the future would be an easy task.

Other Applications

Transfer Function models have also recently been proposed for use in estuary forecasting applications (Environment Agency, 2002c), and have been used operationally in Dumfries, Scotland for flow routing applications for several years (Beven, 2000). However, both of these alternative flow forecasting applications (estuary modelling/flow routing) fall outside the scope of the present study.

The project started in April 2003 and was overseen by an Agency Project Board comprising representatives from Head Office Flood Defence and South West Region (representing all Regions). Draft copies of the report were also reviewed by representatives from the National Flood Forecasting Group (NFFG). Following completion of this project, it is understood that the best practice findings will be incorporated into future updates to the “Real Time Modelling” guidelines.

1.3 Layout of Report

To meet the needs of both flood forecasting practitioners and staff involved in the development and improved application of Transfer Function models, this report is separated into two main sections:

- Section A – Operational Issues
- Section B – Technical Issues

Section A is aimed primarily at Agency staff who are involved in (or interested in) applying Transfer Function models, and provides a general overview of the techniques, a description of best practice uses of these models (where this could be identified) and a brief summary of the main findings from this study. The Factsheets presented in Appendix B may also be of interest when reading this section.

Section B takes a more in depth look at the technical background to this category of model, and is aimed mainly at Agency staff involved in developing and improving the ‘state of the art’ application of these models within the Agency. The mathematical content, and detail provided, is therefore considerably greater in this section.

Section A contains the following main sections:

- Section 2 – Technical Summary – presents essential background material on the main technical issues to consider in development and application of Transfer Function models, including the main categories of model, and approaches to model calibration and real time updating.
- Section 3 – Current Situation – summarises the current use of Transfer Function models within the Agency, and the outcome of literature reviews and consultations during this project regarding the main requirements for improvement within the Agency regarding the use and application of these types of model.
- Section 4 – Towards Best Practice – summarises the main findings regarding best practice use of this type of model (where this could be identified) in the following areas: model selection criteria, model calibration and validation, real time implementation, performance monitoring, and quality assurance.
- Section 5 – Conclusions and Recommendations – presents a brief summary of key findings regarding operational improvements and future R&D needs within the Agency for this category of model

whilst the contents of Section B are as follows:

- Section 6 – Recent Technical Developments – presents a detailed technical description of the main types of Transfer Function model and the current state of the art in real time application of these models.
- Section 7 – Model Accuracy and Uncertainty –describes current knowledge regarding model accuracy and the main sources of model uncertainty, and methods for dealing with uncertainty.

- Section 8 – References and Bibliography – provides a list of references cited in this report together with a more comprehensive Bibliography of relevant reports, books and technical papers.

Finally, two appendices provide supplementary information as follows:

- Appendix A - Summary of Consultations – lists the organisations and individuals who were consulted during preparation of this report, and presents a structured summary of findings from the Agency Regions which use this type of model.
- Appendix B – Model Application Factsheets – presents Case Studies into the use of Transfer Function models within the Agency and elsewhere in the form of Factsheets (in the same format as used in the "Real Time Modelling" guidelines).

Table 1.1, taken from the technical report issued with the "Real Time Modelling" guidelines (Environment Agency, 2002b), also provides a general overview of some of the main issues to consider in using Transfer Function models for flood forecasting applications.

Table 1.1 Model application issues – Transfer Function models (source: Environment Agency, 2002b)

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),	• Better performance may be achieved if the model is driven by effective rainfall, although this may introduce additional uncertainties arising from the model(s) used for rainfall separation based on catchment conditions (which is an active research area) • Often purely data / event based, so no possibility of transfer of parameters between catchments (as with, in principle, a conceptual model, for example), and little or no memory of conditions at previous time steps

	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	• 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 MATH or 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)

Section A – Operational Issues

2 TECHNICAL SUMMARY

This chapter presents a brief technical review of the main issues to consider when applying Transfer Function models for flood forecasting applications.

The chapter begins (Section 2.1) with a summary of the general principles of rainfall runoff modelling then Section 2.2 describes the main categories of Transfer Function rainfall runoff model. Section 2.3 then reviews approaches to real time updating before concluding in Section 2.4 with a summary of the approaches which can be used for model calibration.

Throughout this chapter, mathematical descriptions are avoided but – should more detail be required – an in depth review is provided in Section B of this report. Also, readers who are already familiar with Transfer Function modelling may wish to skim through this chapter before proceeding to the main operational findings of this study, which appear in Chapters 3 and 4.

2.1 Introduction

2.1.1 General Principles

Transfer Function models are a type of input-output model capable of transforming rainfall into runoff. These models have been used within the Agency and its predecessors for flood forecasting applications for more than 20 years. Within the categorisation scheme adopted in the Agency's national guidelines on "Real Time Modelling" (Environment Agency, 2002b) they are included in the general category of 'Blackbox Models'.

Transfer Function models are normally data-based (do not conserve volume) and may include only a limited representation of physical processes (although more sophisticated versions may attempt to capture key processes, such as fast and slow response flow pathways). However, their wide application across a range of industries has led to a sound mathematical and theoretical framework which has been adapted for use in flood forecasting applications.

Figure 2.1 illustrates a simple application of a Transfer Function model within a wider integrated catchment model, in which the Transfer Function rainfall runoff model forecasts flows for input to a flow routing model and a hydrodynamic model. Integrated catchment models of this type are likely to become increasingly widely used within the Agency with the implementation of the National Flood Forecasting System (NFFS) in all Agency Regions over the period 2003-2009.

Some other applications

The name "Transfer Function" describes the transfer of information from one or more observed variables to the variable of interest and arises out of the Systems and Control literature. For flood forecasting applications, the aim is usually to relate forecast flows to observed flows and rainfall at the current and/or previous timesteps. However, flood forecasting is only one of many possible applications, which have included process control in the chemical industry, forecasting stock market trends, control systems in aircraft, and traffic flow management.

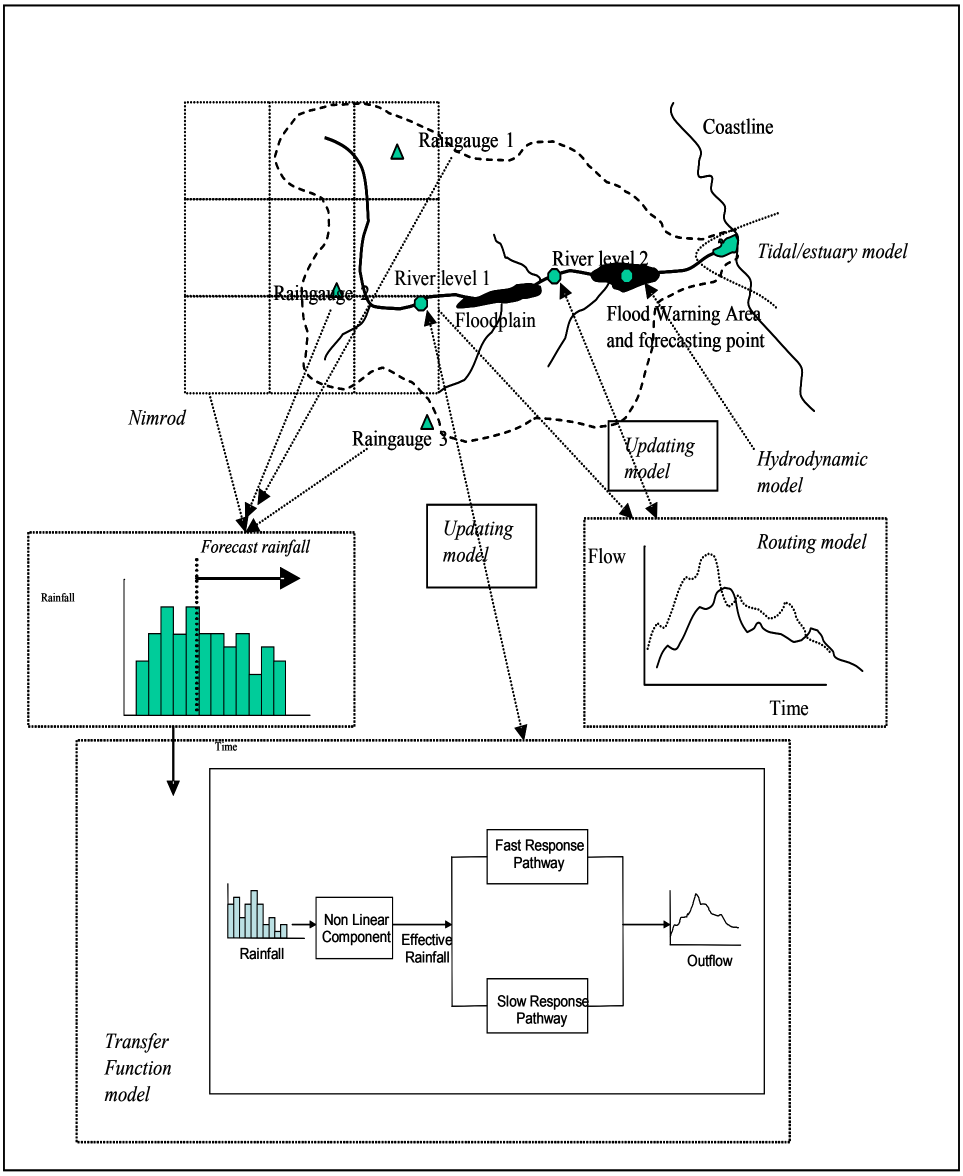

Figure 2.1 A simple example of an integrated catchment model

Transfer Function models may of course also be used on their own to forecast flows to a specific location and as noted later this has been the main application within the Agency to date.

As shown in the figure, models may be driven by observed rainfall (from raingauges or weather radar), or – to increase lead times – by rainfall forecasts (e.g. from the Met Office's Nimrod system). When rainfall forecasts are used, following national guidelines (Environment Agency, 2002a) the use of rainfall forecasts is only recommended up to a maximum lead time of 2-3 hours ahead. Rainfall inputs may be lumped, semi-distributed or fully distributed as follows:

- Lumped rainfall runoff models 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. Key issues to consider include the means of deriving catchment average rainfall, robustness to data loss, and performance for different types of meteorological conditions (frontal, thunderstorms, snow etc).
- Semi distributed models typically divide the catchment into a small number of homogeneous areas which contribute to the flows in the main channel further downstream. An additional key issue to consider is the choice of appropriate contributing areas.

- 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.

Where river level or flow instrumentation is available, forecasts can also be updated in real time to take account of observed levels or flows, often giving significant improvements in forecast accuracy. At present, all operational Transfer Function models within the Agency are of the lumped type.

2.2 Types of Transfer Function Model

Transfer Function models are normally categorised into two main types:

- Linear Models
- Non Linear Models

Although Linear Models are a type in their own right, they also form the basic building block of the more complex Non Linear models. To date, most Transfer Function models used within the Agency have been Linear Models and a simple type of Non Linear Model.

2.2.1 Linear Models

A Linear Transfer Function model relates flows at a point to flows at previous time intervals, and current and previous rainfall. Within the Agency, the standard time interval for telemetered real time data is 15 minutes, and most existing Transfer Function models run at either a 15 minute or hourly time step. This relationship is expressed as in the following example:

$$Q_t = a_1 Q_{t-1} + a_2 Q_{t-2} + \ldots + a_m Q_{t-m} + b_0 R_{t-T} + b_1 R_{t-1-T} + \ldots + b_n R_{t-n-T} \qquad (2.1)$$

where:

Q = flow
R = rainfall
$a_1, a_2 \ldots a_m$ = the model's flow parameters
$b_0, b_1 \ldots b_n$ = the model's rainfall parameters
T = an optional 'false' or 'pure' time delay

and the subscripts t, t-1 etc denote the time interval under consideration. For this example, the model has m flow parameters and n rainfall parameters with a pure time delay of T so is said to have an (m,n,T) structure (or 'order')[1]. In addition, a noise component may be included to model the residual differences between observed and forecast flows (although is not shown in Equation 2.1). The purpose of the pure time delay is to introduce an in-built lag time between rainfall and the corresponding flow, thereby reducing the number of parameters required in the model.

Parsimony

The concept of aiming for a "well measured" number of parameters is referred to as the principle of parsimony, and reflects practical experience that having too many parameters may often poorly represent the process under consideration, whilst too few parameters would undermine the model accuracy.

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[1] Note that the definition of model order varies in the literature, with some authors preferring the n value to refer to the total number of b parameters i.e. also counting the b_0 term

Although the values m and n can take any value, many research publications present models with a relatively small number of parameters e.g. values of $m \le 2$ and $n \le 3$ are typical. However, it should be noted that some Agency models are of higher order as indicated in Chapter 3.

The worked example presented in Table 2.1, adapted from an example given by Reed (1984), illustrates that the real time computation of this type of equation is straightforward, although it is important to note that the resulting flow values (in mm/hr) must be converted to flow units (e.g. cumecs) following this initial calculation.

Indeed, the ease with which calculations are performed was one of the attractions for real time use when Transfer Functions first started to be used for operational flood forecasting in the 1970s and 1980s, although increases in computing power since that time have made this less of a consideration nowadays. Figure 2.2 compares the assumed rainfall profile from Table 2.1 and the estimated flows for this model.

Table 2.1 Example application of a transfer function model with a (1,3,0) structure (the assumed model is $Q_t = 0.9Q_{t-1} + 0.1R_t + 0.4R_{t-1} + 0.2R_{t-2}$ with zero pure time delay)

Time (hrs)	**Observed flow (mm/hr)**	**Rainfall (mm/hr)**			**Individual terms in model response (mm/hr)**				**Model flow (mm/hr)**
		R_t	R_{t-1}	R_{t-2}	$0.9Q_{t-1}$	$0.1R_t$	$0.4R_{t-1}$	$0.2R_{t-2}$	
1	1.00				-	0	0	0	1.00
2		0.1			0.90	0.01	0	0	0.91
3		1	0.1		0.82	0.1	0.04	0	0.96
4		2	1	0.1	0.86	0.2	0.4	0.02	1.48
5		3	2	1	1.33	0.3	0.8	0.2	2.63
6		4	3	2	2.37	0.4	1.2	0.4	4.37
7		3	4	3	3.93	0.3	1.6	0.6	6.43
8		2	3	4	5.79	0.2	1.2	0.8	7.99
9		1	2	3	7.19	0.1	0.8	0.6	8.69
10		0.1	1	2	7.82	0.01	0.4	0.4	8.63
11			0.1	1	7.77	0	0.04	0.2	8.01
12				0.1	7.21	0	0	0.02	7.23
13					6.51	0	0	0	6.51
14					5.85	0	0	0	5.85
15					5.27	0	0	0	5.27
16					4.74	0	0	0	4.74
17					4.27	0	0	0	4.27
18					3.84	0	0	0	3.84
19					3.46	0	0	0	3.46
20					3.11	0	0	0	3.11

Despite this apparent simplicity of application, two important points to note are that:

- The process for deciding on the structure and coefficients of the model is considerably more complex (although facilitated by software packages such as MATH, Matlab or CAPTAIN – see later)

- For certain model structures, and combinations of parameters, the model output can be oscillatory or even generate negative flows

Due to the issue of oscillatory or negative outputs, 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 model structure still remains as shown in Equation (2.1) but the relationship between the a_i parameters is constrained to achieve a stable response, with a value of m=3 typically used.

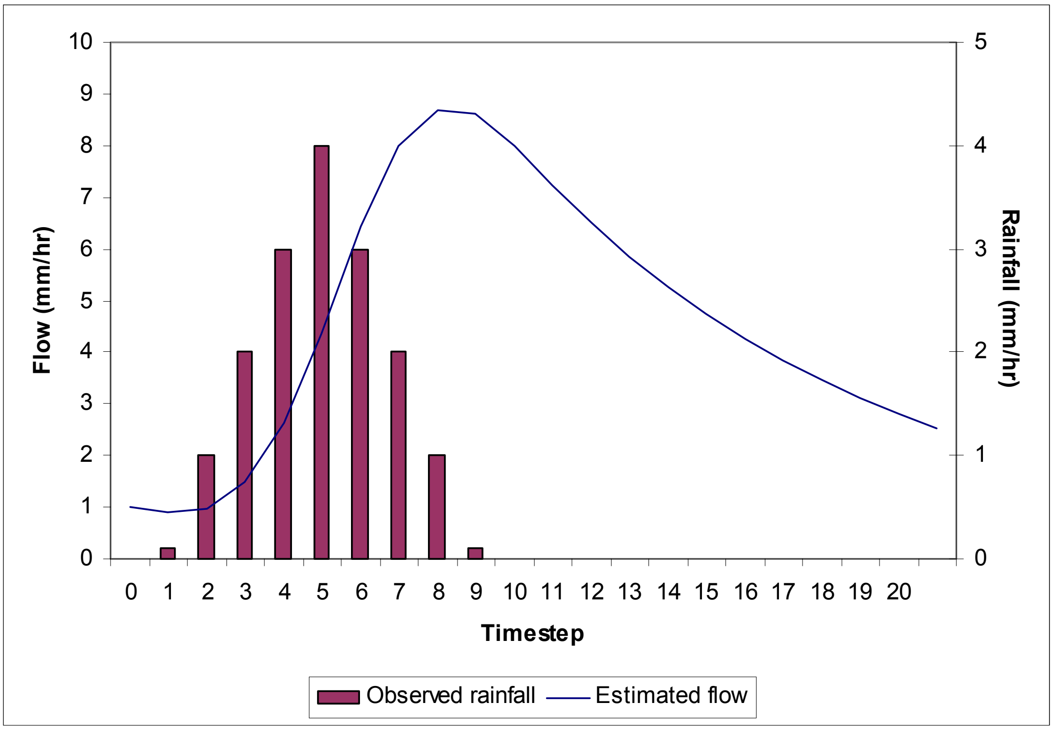


Figure 2.2 Comparison of observed rainfall and forecast flows from Table 2.1

One further issue with linear Transfer Function models is whether the rainfall inputs should consist of total rainfall or effective rainfall (i.e. total rainfall less an assumed baseflow component). At present, most operational Transfer Function models used within the Agency use total rainfall as an input, leading to possible overestimates of runoff if catchment antecedent conditions are drier than for the events in the calibration dataset. However, counterbalancing this effect, it could be argued that, for the really big flood events, then the catchment rapidly becomes saturated so that, provided the model is calibrated for the largest events, the total rainfall provides a reasonable input to the model.

There are many possible methods for calculation of effective rainfall and these are outlined in the following section, with a more detailed technical discussion presented in Section B.

Comparisons with the FEH Unit Hydrograph approach

Hydrologists who have used the Unit Hydrograph based rainfall runoff approach included in the Flood Estimation Handbook (FEH) will note many similarities with the Linear Transfer Function modelling approach; for example, the use of a lumped rainfall input, the issue of rainfall separation, and the assumption of a linear relationship between effective (or total) rainfall and flow (less a baseflow component in the case of the FEH). The impulse response function of a Transfer Function model is also equivalent to a scaled version of the underlying instantaneous unit hydrograph. For flood forecasting applications, Reed (1984) notes that perhaps the main advantages of the Transfer Function approach compared to the Unit Hydrograph are that:

- The model formulation is more efficient in the sense of having fewer parameters to be calibrated
- The model output can be expressed explicitly in terms of flows, facilitating application for real time use
- The model output is tolerant to data loss, being able to reinitialise at any time step during an event
- The model output can readily be updated in real time, bringing potentially major gains in forecast accuracy

2.2.2 Non Linear Models

To address the issue of the influence of antecedent conditions, research on Transfer Function models has in recent years focussed on more complex model structures which attempt to account for this effect i.e. so called Non Linear models. Two widely used techniques are:

- Preprocessing of total rainfall to net (or effective) rainfall via an algorithm variously called a “rainfall excess” or “effective rainfall” component in the literature
- Introduction of a second slow response flow pathway to represent baseflow influences

Figure 2.3 illustrates a typical model structure incorporating both of these elements.

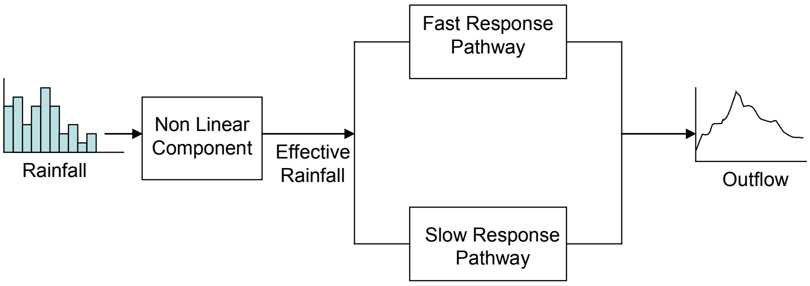


Figure 2.3 Illustration of a possible configuration for a non linear Transfer Function model

Both the fast and slow response pathways are typically implemented as Linear Transfer Function models, although now as functions of effective rainfall, rather than total rainfall. The separation of flows into the fast response pathway can be either continuous (the usual approach) or can switch in above a certain threshold, depending on some measure of catchment state (e.g. Catchment Wetness Index).

Similarities with Conceptual Rainfall Runoff Models

Readers familiar with Conceptual Rainfall Runoff models will note a marked similarity between this type of model structure and a typical conceptual model incorporating soil moisture storage, surface runoff and baseflow stores. Indeed, some types of conceptual model implement aspects of the model in the form of a Transfer Function (for example the linear reservoir, either singly, or in series or parallel, is widely used in conceptual models). For a non linear Transfer Function, physically meaningful quantities can also be identified from the model structure, such as the partition of flows between the fast and slow pathways (a pseudo runoff coefficient), and the residence times (or time constants) and travel times (or advective times) in each pathway. However, compared to a Conceptual Model, the non linear Transfer Function model retains the data-based concept, in that it maintains no memory of the state or storage at previous timesteps (although as described below some variants do maintain state to a limited extent in the effective rainfall estimator).

Regarding the Effective Rainfall estimator, a number of approaches have been proposed in the research literature and – as described in Chapter 3 – several have been evaluated for possible use within the Agency. Following the data-based approach, effective rainfall is generally related to total rainfall via one or more parameters which can – in principle – be observed in real time and which have an influence or dependence on catchment state.

Some possible candidates for inclusion include current flows, evaporation, or air temperature (as a surrogate for evaporation). The full technical background to these approaches is presented in Section B but, in general terms, the main methods which have been proposed for Agency use are:

- Soil Moisture Accounting methods – which use a simple soil moisture accounting model to relate effective rainfall to functions of total rainfall and evaporation (or some surrogate variable e.g. air temperature).
- The State Dependent Parameter (SDP) approach – developed at Lancaster University in which the rainfall separation is performed on the basis of a function of observed flows at the current timestep (e.g. a power law function).
- Constant and Variable proportional loss methods – in which the effective rainfall is assumed to be either a fixed value or a proportion of the total rainfall dependent on catchment state at the start of the event or computed during the event.

Techniques have also been proposed in which the model parameters themselves are varied during an event but these have been classified as a type of real time updating and are discussed in the following section.

2.3 Real Time Updating

Real time updating uses observed river level or flow data to adjust forecasts to take account of any discrepancies between observed and forecast flows up to the present time step. Updating procedures therefore make use of the inherent information content available in real time to reduce the uncertainties associated with the forecast results. Figure 2.4 illustrates the general principles of real time updating.

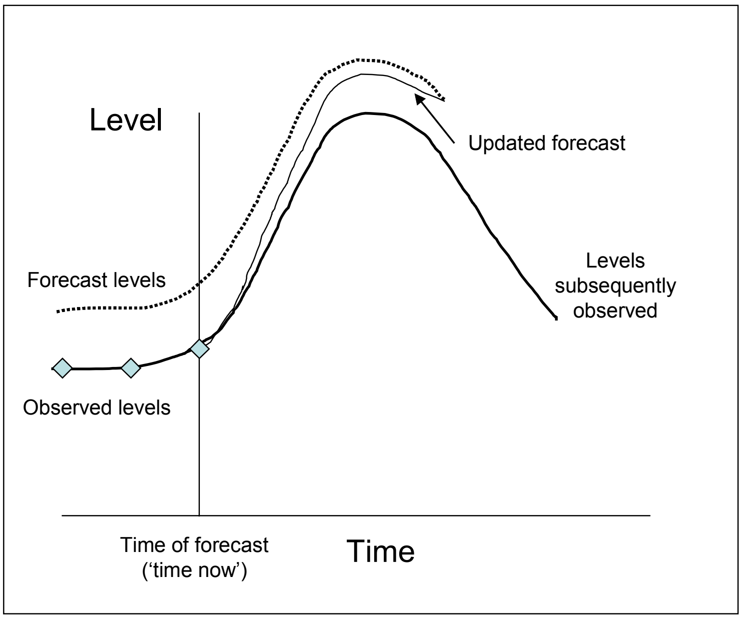


Figure 2.4 – Illustration of the principle of real time updating of forecasts

In this example, the updating routine has had the effect of adjusting the updated forecast so that the correction decays to zero at the maximum lead time of the forecast (although other types of adjustment are possible).

The "Real Time Modelling" guidelines (Environment Agency, 2002b) strongly recommend the use of real time updating in real time forecasting applications, and describe three main approaches to updating as defined in the Table 2.2.

Table 2.2 Main approaches to real time updating (source: Environment Agency, 2002b)

Method	Basic principle/assumption	Types of Real Time Model which can use this approach
Error prediction	The differences between observed and predicted flows are assumed to vary in a consistent way e.g. consistent overestimation. A statistical model can then be fitted to the 'observed' errors and used to forecast future errors.	Can be used for all rainfall runoff and routing types in principle including hydrodynamic models
State updating	The internal stores, or indicators of current conditions (e.g. flows for soil moisture), can be adjusted in real time to correct for errors in rainfall data etc	Suitable for conceptual and transfer function models, and some types of routing model. Possible for hydrodynamic models by adjusting tributary/upstream inflows or reservoir levels etc
Parameter updating	The parameters of the model can be adjusted in real time to account for changes in model performance during an event	Not recommended for conceptual models since it implies an incorrect initial calibration. A possibility for updating non linear Transfer Function models and hydrodynamic models (e.g. via roughness coefficients)

Although there are several important implementation issues to consider (see Chapter 4), all of these techniques can in principle be used for updating Transfer Function models.

Table 2.3 summarises some of the methods which are proposed in the research literature (and which are described in more detail in Section B, together with some more sophisticated stochastic techniques).

The majority of these techniques require calibration of the updating routines either jointly with the model calibration, or as a separate exercise once the initial calibration has been performed, and these issues are discussed in the following section. Real time updating methods also often require suitable run-time software to be available which to date has been a major constraint in application of these techniques within the Agency (see Chapter 5).

Table 2.3 Possible approaches to updating transfer function models

General Category	Type / Name	Basis of Method
Error prediction	Graphical Correction	Adjustments 'by eye' or on computer for any trends observed in the differences between observed and forecast flows up to the current time step e.g. timing or magnitude differences
	Time series model	A separate statistical model calibrated on the 'noise' component identified by comparing forecast and observed flows, and typically of the Auto Regressive Moving Average (ARMA) type
	Pattern Matching	Repeated sampling techniques applied in real time to identify adjustments to the input rainfall data (timing and magnitude) so that the output better matches observed flows
State updating	Flow Substitution	Substitution of observed (telemetered) flows for estimated flows wherever available at each time step
	Adaptive (or Time Varying) Gain	Computation at each time step of a gain parameter which is applied to all input rainfall values
	Kalman Filter	Use of Kalman Filter to estimate the optimal state (i.e. flow) based on available data
Parameter updating	PRTF approach	Manual adjustment of three additional parameters which define the shape, magnitude and timing of the hydrograph; either 'by eye' or by selecting predefined values based on a look up table of Catchment Wetness Index values
	Transfer Function Noise	Inclusion of a noise component (e.g. ARMA(p,q)) in which the autocorrelation and/or random parameters in the noise model component are varied during an event (similar to error prediction)
	Time Variable Parameter (TVP)	Automated adjustment of the rainfall (b_i) parameters in real time using recursive estimation
	Genetic Algorithms	A structured form of random sampling in which parameters move towards their optimum values guided by pre-defined rules for 'evolving' between each successive sample. Also, methods which combine classical optimisation routines with the Genetic Algorithm approach (e.g. the Shuffled Complex Evolution approach).

2.4 Model Calibration and Validation

The real skill in using Transfer Function models is in the model calibration, although this process can be greatly assisted by well designed calibration procedures. It is also at this stage that software limitations become apparent; for example, although such software is available in the research community, at present no Agency Region has the tools available to calibrate parallel pathway Transfer Function models and – even if this was available – there is no operational real time software platform available for using these models in flood forecasting applications.

However, as described later, steps are being taken in some Agency Regions to enhance the functionality of existing software (see Section 3), whilst the NFFS will provide the capability for third party software developers to develop module adaptors which would enable the required software to operate within the NFFS.

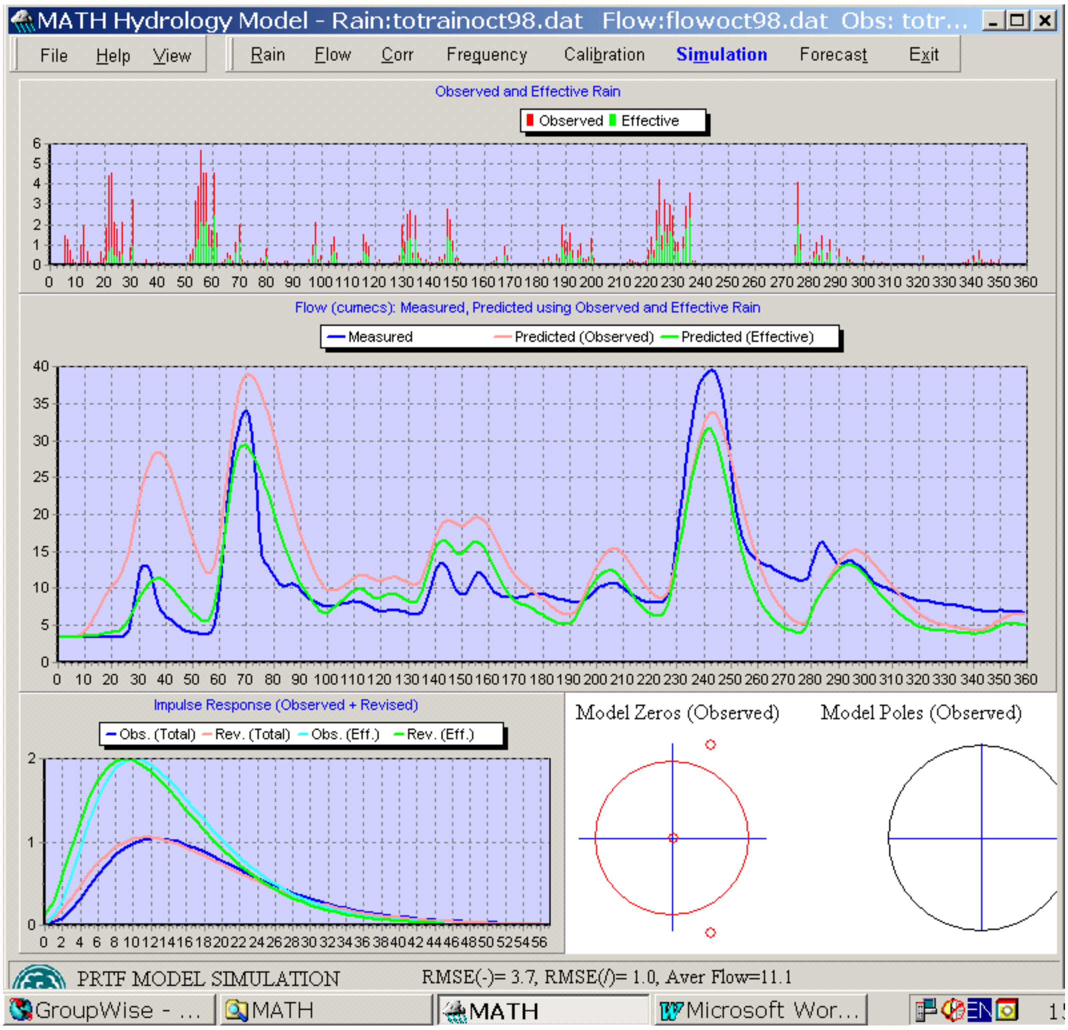
If these limitations are set aside, then – assuming that a Transfer Function model is appropriate for the modelling problem - ideally model calibration would be performed using the following steps based on an understanding of the catchment response, analyses of historical data, and exploratory studies using the calibration software:

- Stage 1 - General Model Identification – is a linear, non linear, parallel pathway etc model to be used and will it include updating and initialisation components ? The outcome of this stage is the development of a preliminary (or raw) model.
- Stage 2 - Model Structure Identification – what structure of model is to be used for each component of the model ? The outcome of this stage is the identification of a parsimonious (site-specific) model structure.
- Stage 3a - Model Parameter Optimisation – calibration of the individual parameters in the model
- Stage 3b - Model Updating Routine Calibration – optionally calibration of the parameters in the real time updating component of the model (unless included implicitly in the previous step)
- Stage 3c - Model Validation – against flood events not included in the original calibration
- Stage 4 – Model Testing and Integration – integration and testing (e.g. for robustness) in the real time system environment (e.g. NFFS) of models developed in a stand-alone calibration environment. This stage will not be discussed further in this report.

It should also be noted that the Agency is developing a formalised modelling procedure for flood forecasting, which will provide a generic framework for model development. It is understood that the above procedures conform with these recommendations.

Modern calibration software typically provides graphical and other tools for performing Steps 2 and 3a (and sometimes Step 3b) in a single package. For Transfer Function modelling (see Section B), some widely used calibration or optimisation techniques include the recursive least squares approach (RLS) and simplified recursive instrumental variable approach (SRIV).

Figure 2.5 shows an example of the calibration user interface for a calibration package (MATH) which uses the RLS approach.



PRTF MODEL SIMULATION RMSE(-)= 3.7, RMSE(/)= 1.0, Aver Flow=11.1

Figure 2.5 Example output from the MATH rainfall-runoff calibration software (v1.13) using rainfall runoff data from the period 22nd October to 5th November 1998

In the figure, it is of particular interest that an initial false peak is predicted when using total rather than effective rainfall due to the initial dry conditions of the catchment.

Compared to many other types of forecasting model (e.g. flow/discharge routing, conceptual rainfall runoff models), Transfer Function models are usually (but not always) calibrated on individual flood events, and do not consider performance for moderate to low flow periods between events. This difference arises from the data-based nature of the models, and the lack of any significant memory within models of past conditions (i.e. before the previous few time steps). However, for all except the simplest Linear models, model initialisation to take account of antecedent catchment conditions is an important consideration.

The criteria for model optimisation also need to be taken into account; for example, is the model to be optimised for the magnitude and/or timing of peak flows, or some measure of the goodness of fit for the full hydrograph ? Also, should the optimisation be performed in simulation mode (i.e. with no updating), or jointly for the model and updating parameters and, in the latter case, should the optimisation be performed for a given forecast lead time or for the current time step ? Other questions include the number of events to use for calibration, and the use of independent events (outside the original calibration) for model validation.

These and other related model calibration issues are discussed in Chapter 4 and Section B whilst Table 2.4 summarises some of the main model optimisation criteria which appear in the literature on flood forecasting applications of Transfer Function models.

Table 2.4 Some commonly used model identification and optimisation criteria for Transfer Functions used for flood forecasting applications

Criterion	**Description**
Peak Flow	Maximum flow reached
Timing of Peak	Timing of peak flow
Volume under Hydrograph	Volume above a threshold
Root mean square error (rmse)	Square root of the sum of the squares of the differences between observed and similated flows
Nash Sutcliffe Efficiency (R^2)	Measure of the proportion of variance explained by the model
Akaike Information Criterion (AIC)	Performance measure related to the model order, number of data points, and the rmse
Young Information Criterion (YIC)	A development of the Akaike Information Criterion
Coefficient of Determination	Ratio of the explained variation to the total variation.
Explained Variation	A variation of the rmse measure

3 CURRENT SITUATION

This chapter describes the current use of Transfer Function models within the Agency, and the main requirements for improvement in the use and application of these types of model identified during this project.

The chapter begins (Section 3.1) with a brief review of current applications of the Transfer Function models for flood forecasting applications in South West, North West, Anglian and Southern Regions. Section 3.2 then discusses the currently available system environments in these Regions. Finally, Section 3.3 discusses the main issues regarding operational use of Transfer Function models identified from the literature review, an assessment of relevant Agency reports, and the consultations with Agency staff performed during this project.

More background information on Agency applications of Transfer Function models can be found in Appendix A, and examples of specific applications in the Agency and other organisations (e.g. SEPA) can be found in the Factsheets presented in Appendix B as follows:

- River Tone, South West Region
- River Greta, North West Region
- Dumfries, SEPA

3.1 Environment Agency Applications

Appendix A presents a detailed review of current applications of Transfer Function Models within the Agency under the following headings:

- History
- Types of Models
- Real Time Updating
- Model Calibration and Verification
- System Environment
- Operational Applications
- Operational Issues
- Future Development Plans

This section presents section presents a general summary of this information. Appendix A should be referred to for more details on the various topics which are discussed for each Region.

3.1.1 History

Transfer Function models have been used within the UK for at least twenty years. Table 3.1 indicates some key dates in this process.

Table 3.1 Indicative history of Transfer Function modelling for rainfall runoff modelling in the Environment Agency and its predecessors

Year(s)	Organisation	Description
1970s	Wessex Water	Operation of simple Non Linear Transfer Function models
Late 1980s	Anglian NRA	Calibration and implementation of simple Linear Transfer Function models for flood forecasting applications
1991	Salford/Bristol University	Development of the PRTF variant of the Linear Transfer Function model
Early 1990s	Wessex NRA North West NRA	Real time implementation of PRTF models using the WRIP system
Late 1990s	Southern Region	The "Flood Forecasting Platform" was introduced and included the option to run Transfer Function models
2000	CEH (Wallingford)	R&D report W242 described an intercomparison of Conceptual, Transfer Function and other types of rainfall runoff models used in the Agency for flood forecasting applications
2002	Agency Met Office Atkins Water Edenvale Modelling JB Chatterton	National "Real Time Modelling" guidelines developed a structured approach for selecting modelling solutions, including Transfer Function based solutions.
2003	Agency Atkins Water	Present study

3.1.2 Types of Models

Table 3.2 summarises the types of Transfer Function rainfall runoff model which are presently used within the Agency:

Table 3.2 Current uses of Transfer Function models for rainfall runoff modelling in the Agency

Type	Organisation	Description
PRTF	South West Region North West Region	Standard PRTF model as implemented in WRIP, with the option for effective rainfall preprocessing using the IHACRES approach (South West Region only)
Linear	Anglian Region North West Region	Classical Linear Transfer Function models
Non Linear	Southern Region	Simplified, early versions of the Lancaster DBM approach

3.1.3 Real Time Updating

Although three Regions have the facility for real time updating of Transfer Function models, this feature is rarely used operationally since it must be operated manually (with staff time/expertise issues during a widespread flooding event).

In South West and North West Regions, the method used is to manually adjust the three parameters in the PRTF model which control the shape, volume and timing of the hydrograph. South West Region has also calibrated some models with updating in mind, such that look up tables are available relating the updating parameters to Catchment Wetness Index at the start of the event. However, this process has not yet been used operationally during a flood event.

In Anglian Region, although an automated updating method is available (using a variable gain parameter), this is operated manually at present due to the uncertain results which can be obtained from the automated procedures.

3.1.4 Model Calibration and Validation

Provided that a decision has been taken on the general type of model to use (Linear, Non Linear etc) then the issues which need to be considered in model calibration include:

- The approach to parameter optimisation
- The calibration criteria used
- The software package used (if any)

Table 3.3 shows the general approaches taken in the four Agency Regions which currently use Transfer Function rainfall runoff models for flood forecasting applications:

Table 3.3 Agency approaches to Transfer Function model calibration

Issue	South West	North West	Anglian	Southern
Parameter Optimisation				
Recursive Least Squares	Yes	Yes	Yes	Unknown
Manual adjustments	Yes	Yes	Yes	
Calibration Criteria				
Root mean square error	Yes	Yes	Yes	Unknown
Peak flow	Yes	Yes		
Software Package for Calibration				
MATH	Yes	Yes		
TFCAL		Formerly	Yes	

Table 3.4 summarises the overall model structures (m,n,T) identified from the examples of calibrated models which were provided by the Agency Regions during this project and the "Real Time Modelling" guideline project (Environment Agency, 2002b).

Table 3.4 Indicative sample of the model structures surveyed as part of this project (the values shown are the number per Region of that type, whilst m, n are defined in Section 2.2.1)

Model Structure		South West	North West
M	n		
0	1		
0	2		
0	3		1
1	1		
1	2		
1	3		36
2	2		
2	3		1
2	4		
3	0	1	
3	1		
3	2		
3	3	2	

Whilst these are only partial samples of the models which are used in each Region, it can be seen that there can be wide variations in model order, depending on the types of model and calibration software used.

3.1.5 System Environment

At present, three software platforms are used within the Agency for the real time operation of Transfer Function models. These systems are described in detail in Section 3.2 and Appendix A but may be briefly summarised as follows:

- WRIP – South West, North West - originally developed by the University of Salford in the early 1990's (and subsequently the University of Bristol) for the integrated display of weather radar, rain gauge and river gauging station data, and to act as a real-time forecasting platform for Transfer Function rainfall-runoff models.
- FFP – Southern - developed initially in the late 1990s by Water Resources Associates, this is a pc based system which takes real time telemetry data and includes graphical and reporting options for model output and is capable of running several types of model (Transfer Function, conceptual, flow routing)
- Anglian Region – a purpose made in-house system developed in the late 1980s for running the Linear Transfer Function models used in the Region.

With the introduction of the NFFS, it is anticipated that these systems will be gradually phased out over the period 2003-2009 and their modelling capabilities migrated to the NFFS.

3.1.6 Operational Applications

The consultations suggested that the following numbers of Transfer Functions are presently used within the Agency:

Table 3.5 Indicative estimates for the numbers of Transfer Function models used or available for flood forecasting applications within the Agency

Region	Operational	Calibrated
South West	33	> 100
North West	3	>40
Anglian	24	?
Southern	10	?

Note that Table 3.5 distinguishes between models which are used operationally for real time flood forecasting, and those which have been calibrated off-line, but are not yet implemented.

One further point to note is that the consultations suggested that in recent years there have been few, if any, instances where the output from a Transfer Function model has been used to issue a Flood Warning. Instead, the models are used by Flood Forecasting staff as a guide to likely future trends and to help in deciding on what advice to give to Flood Warning staff.

This situation contrasts with the present situation with Conceptual rainfall runoff models where the model forecasts are much more closely integrated with operational procedures. For example, North East Region have several examples of fast response catchments where forecasts from Conceptual Models are built into Flood Warning Procedures as the primary means of issuing warnings to high risk locations (provided of course that real time updating is used at those locations).

3.1.7 Operational Issues

Performance Monitoring is essential to evaluate the performance of models in operational use, and has a pivotal role in assisting with future improvements to individual modelling solutions, and in identifying generic problems or issues associated with types of model, software, staff training requirements etc. Whilst a forthcoming R&D Project (R&D Project T32) will examine the performance measures of Accuracy, Reliability and Timeliness, the consultations showed that a range of performance monitoring methods are currently being developed in the Regions, including peak timing and magnitude assessments, and Contingency Tables based on flood warning thresholds (e.g. Severe Flood Warning levels).

It is believed that none of the Agency Regions contacted during this project operate a formal Quality Assurance process for model or software development themselves, other than the systems which may be operated by any suppliers which they use (consultants, software houses etc). However, both South West and North West Regions have a process of documenting each new model developed in model calibration reports, and all Regions use well established suppliers for existing software systems.

During the consultations, the following issues were considered regarding the Technical Expertise within the Regions which use Transfer Function models:

- Years of experience with this type of model
- Numbers of staff able to calibrate and further develop models
- Links to research organisations with expertise in Transfer Function modelling
- User of external software developers
- Use of consultants for model calibration and development

Table 3.6 summarises the main findings in these areas:

Table 3.6 Indication of technical expertise in transfer function modelling in the Agency Regions using these models operationally

Issue	South West	North West	Anglian	Southern
Years of TF Experience	>20	> 10	>10	3
Number of Staff (approx.)	2	3	1	1
Links to Research Organisations	Bristol	Bristol, Lancaster	Unknown	Unknown
External Software Development and Support	Plan B	Plan B	In-house	Water Resources Associates
Use of Consultants	Yes[+]	Yes	No	Yes

+ Full time secondment only

3.1.8 Future Development Plans

The consultations suggested that, following a proliferation of activity in the 1980s and early 1990s, the development of Transfer Function models for flood forecasting applications has largely been ‘on hold’ within the Agency and its predecessors until the past 2-3 years. However, all four Regions which use these models have improvement plans for these models and for their wider use in operational flood forecasting. These developments are described in Appendix A whilst Table 3.7 provides a brief summary of the main findings.

Table 3.7 Indication of future development plans in the Agency Regions using transfer function models operationally

Region	Description
South West	• Investigations into effective rainfall estimation • Investigation into real time updating procedures • Software implementation of updating and effective rainfall • Concurrent display of raingauge and radar based flows • Development of improved performance monitoring procedures • Integration of performance monitoring into routine procedures • Continued development and real time implementation of models and integration into Flood Warning Procedures • Real time transfer of forecasts to the telemetry system
North West	• Continued calibration of models for new high risk sites • Evaluation of the potential use of Non Linear models • Automated estimation of Catchment Wetness Index (CWI) and model selection according to CWI
Anglian	• Porting of existing models to the Regional forecasting system (Anglian Flood Forecasting and Modelling System - AFFMS)
Southern	• None planned

3.2 System Environment

The System Environment is the network of computers, software, telemetry systems etc which support the operation of models in real time. Typically this type of system will handle data input from telemetry, present model output in the form of graphs, maps, reports etc, and will possibly be capable of raising alarms and transferring both alarms and forecasts to telemetry systems for viewing alongside the real time data.

Although the simpler types of Transfer Function model could – in principle – be operated on spreadsheets or stand-alone software with manual data input, in practice this approach is not practicable in a major event given the many other demands on staff time.

The automated systems which are currently used within the Agency are WRIP (South West, North West), FFP (Southern) and a bespoke system in Anglian Region (described in Appendix A3) The NFFS will support the operation of all model types which are selected for modularisation following its implementation over the period 2003-2009. These systems are briefly described in the following sections.

3.2.1 WRIP

The Wessex Radar Information Processing system (WRIP) – later renamed the Weather Radar Information Processing system - was originally developed by the University of Birmingham, then the University of Salford and subsequently the University of Bristol. The system is used in South West and North West Regions with maintenance and support provided by Plan B (UK) consultants. The hardware environment was originally Unix but has now also been ported to a pc environment.

The system combines radar and raingauge rainfall measurements with telemetered river flow data and has at various times incorporated rainfall runoff models, flow routing models, and tidal models. However, the versions presently operated in South West and North West Regions only use Transfer Function models operationally. Associated with WRIP is a separate model calibration environment called MATH.

The basic functionality of the real time component of the system includes:

- the ability to replay weather radar events;
- Thiessen polygon estimates of area rainfall from raingauges around the catchment or a rainfall fitting surface;
- estimation of catchment rainfall from radar data;
- display of telemetered raingauge and river level/flow data;
- ability to run ‘what if’ scenarios using radar, raingauge and user defined values (e.g. no more rainfall, average of the past six hours, outputs from a storm forecasting model, manually entered profiles);
- the facility to estimate the hourly Catchment Wetness Index (CWI) and Soil Moisture Deficit (SMD) using a simple water balance accounting approach and user supplied weekly MORECS values for SMD and display the CWI on maps and as timeseries graphs.

WRIP display functions include the ability to display maps showing station locations, rainfall-flow time series plots, and plots comparing hydrographs at different stations. With the exception of the Bristol Avon model for South West Region (see Appendix A1), the currently operational WRIP models are all ‘stand alone’ and are not combined into integrated catchment models with other types of model e.g. routing or hydrodynamic models.

For the PRTF component of the system, a number of developments are currently planned by South West Region as described in Appendix A.

3.2.2 FFP

The run time environment used in Southern Region for flood forecasting models is the Flood Forecasting Platform (FFP) software developed initially by Water Resources Associates. This is a pc based system which takes real time telemetry data and includes graphical and reporting options for model output.

3.2.3 NFFS

The National Flood Forecasting Modelling System Strategy NFFMS (Environment Agency, 2002c) aims to converge on a nationally consistent approach to flood forecasting across England and Wales through the introduction of ‘open shell’ forecasting systems in which the main functions of the shell are to provide:

- an interface to other Agency systems;
- validation and editing modules for data received from other Agency systems;
- Forecasting Module calibration utilities;
- Forecasting Module Dataset (Static and Dynamic) processing through published interfaces;

- a platform for Forecasting Modules and Forecasting Module Datasets;
- an interface to existing and future Forecasting Modules by the use of Adapters and a generic interface;
- a short term operational data storage facility for raw data and processed/forecast data;
- an audit trail;
- displays of Forecasting Module output; and
- a mechanism for raising forecast based alarms and communicating these to a telemetry system.

Here, a Forecasting Module is essentially a level or flow forecasting model (e.g. a Transfer Function model) which translates observed or forecast rainfall, flows etc into forecasts of river levels and flows at a Forecasting Point. A Forecasting Module Dataset consists of the model parameters, data etc required to operate the model.

This functionality is currently being implemented using a system known as the NFFS. Whilst the NFFS is associated with a range of operational benefits owing to its open architecture, for Transfer Function modelling the main relevant advantages include:

- A framework for combining individual models into networks of models to produce integrated catchment models
- The ability for third-party software suppliers to more easily adapt their models to run on and interface with Agency forecasting and telemetry systems
- The ability for Regions to share types of models, once the original Forecasting Module has been developed nationally or in another Region
- Easier implementation of real time updating procedures
- Greater consistency in the use of and application of models between Regions

Three Regions (Midlands, Southern and North East) are (at the time of writing) about to implement these systems, whilst North West, Wales, Thames and South West Regions are scheduled for implementation of the system during a second phase lasting from 2005 to 2007, with Anglian Region following in 2008.

3.3 User Requirement for Improvements

During the course of this review, a number of issues became apparent concerning the use of Transfer Function models within the Agency. Either these were raised directly by Agency staff or in consultations with research groups, or were identified during reviews of previous Agency strategy and R&D reports which included some discussion of Transfer Function models.

This section attempts to collate all of this information and follows the same general format as Section 3.1 but excluding the ‘History’ subsection i.e.

- Types of Models
- Real Time Updating
- Model Calibration and Validation
- System Environment
- Operational Applications
- Operational Issues
- Future Development Plans

Sources of information or comments are not identified other than where this might provide additional background information which could not be incorporated into the present report due to lack of space etc. Also, although only providing a rough indication, it is perhaps useful to see the number of issues which were raised in each of these categories and this is indicated in the following Table 3.8:

Table 3.8 Numbers of issued raised in the consultations and review by general subject area

General Subject Area	Number of issues raised
Types of Model	4
Real Time Updating	5
Model Calibration and Validation	9
System Environment	3
Operational Applications	1
Operational Issues	7
Future Development Plans	3

Clearly, the issues of type of model (and model selection criteria), real time updating, model calibration and validation, and operational issues (performance monitoring, quality assurance etc) are of key importance to Agency staff.

3.3.1 Types of Models

Issue 1.1: At present, the Agency only uses a small proportion of the types of Transfer Function model which have been developed for flood forecasting applications. This is due mainly to limitations with software and/or the System Environment since, although more sophisticated models have been evaluated off-line by Agency staff, it has not been possible to implement them operationally.

Issue 1.2: Agency staff report that more guidance is required on the type of Transfer Function model to use for a given flood forecasting problem, and the limitations and strengths of each approach, whilst recognising that with current knowledge it may not be possible to give definitive guidelines in all situations. The recently issued “Real Time Modelling” guidelines meet this requirement and can be refined in future updates according to the experience gained from their application.

Issue 1.3: For some forecasting problems, there is a clear wish for the Agency to adopt Non Linear models which estimate effective rainfall to help account for catchment antecedent conditions, and which include some representation of baseflow contributions (where relevant).

Issue 1.4: Regarding methods for allowing for antecedent conditions, there are various views on how to proceed, ranging from the pragmatic approach of using some type of conceptual soil moisture accounting procedure (e.g. estimating Catchment Wetness Index), to the view that Transfer Function models should remain entirely data-based, and not rely on memory of previous state. In the latter case, there are mixed views on which are the most appropriate surrogate parameters to use (e.g. flow, air temperature etc).

3.3.2 Real Time Updating

Issue 2.1: Within the Agency, automated updating procedures are not used in any of the four Regions operating Transfer Function models, in contrast to the situation with other types of model (e.g. Conceptual, Flow Routing), where this has been routine for many years. Again, the problem has been with lack of suitable run time software.

Issue 2.2: Agency staff report that guidance is required on the most appropriate types of updating procedures to use e.g. error prediction, state updating, parameter updating (and individual approaches within these general categories).

Issue 2.3: The present manual updating methods used in South West and North West Regions, whilst useful in principle, are impractical to apply in a widespread flood event such as October 2000, and results are very dependent on the skill level and experience of the operator.

Issue 2.4: A view amongst many researchers is that models should be calibrated with a given lead time in mind, including the updating component (e.g. 1 hour ahead, 3 hours ahead). However, at present, all Agency models are calibrated in simulation mode without updating.

Issue 2.5: Whilst one of the attractions of Transfer Function models is that they are event-based (i.e. can be started up at any time without initialisation), this does mean that they are vulnerable to the impacts of data errors (e.g. spikes or drop outs in rainfall or flow data). Future developments should include improved ways of safeguarding against this problem e.g. filtering and other quality control of incoming data in real time.

3.3.3 Model Calibration and Validation

Issue 3.1: Several different approaches to model calibration have been identified within the Agency during this review and more guidance is required on ‘best practice’. Examples include; calibration on a single event or many events, optimising parameters across all events or averaging parameters from each event, optimising on the full hydrograph or the timing and magnitude of the peak etc.

Issue 3.2: Agency staff report that guidance is required on the appropriate model time step to use in a given situation. Also on related issues such as the number of calibration and validation events required, appropriate model structures, and the calibration criteria to use (R^2, peak flow etc).

Issue 3.3: For flood forecasting applications, Transfer Function models are typically used to forecast the likely peak value, and the times that critical threshold levels are likely to be crossed (e.g. a Severe Flood Warning level). This would suggest that models should be optimised for predicting the magnitude and timing of the peak, and the shape of the rising limb of the hydrograph (although this might be at the expense of more accurate volume and duration estimates). However, most existing calibration methods focus largely on the peak and/or the whole hydrograph and do not consider the rising limb separately.

Issue 3.4: In some locations, weather radar data and forecasts are the preferred rainfall data source for operating Transfer Function models. However, until the latest HYRAD system became available (in April 2002), the difficulty in obtaining historical weather radar data meant that models have traditionally been calibrated using historical raingauge data, but then sometimes operated in real time using radar data. Given the likelihood of differences (both random and systematic) between these two measurement systems, this practice may lead to large errors in model output.

Issue 3.5: Agency staff report that the lack of accurate high flow ratings at many sites affects the accuracy of model output, and restricts the number of sites for which new models can be developed. Guidance is also required on the use (or extrapolation) of model outputs beyond the initial calibration range e.g. for extreme events.

Issue 3.6: Amongst researchers, there is an ongoing debate concerning the most appropriate optimisation algorithms to use for automated optimisation of Transfer Function models (RLS, SRIV etc). However, it should be noted that there is unlikely to ever be a best overall technique for all circumstances but even here the principle of 'horses for courses' should be applicable.

Issue 3.7: The brief review of current Agency models (see Section 3.1.4) shows that there are wide variations between Regions in the structure of models used, with some Regions developing models with fewer parameters than others (i.e. more 'parsimonious' models – see Section 2.2.1). Agency staff report that in some cases this is more a function of the calibration environment which is available, rather than an intention to achieve any particular model structure during calibration.

Issue 3.8: It is generally agreed that current Agency procedures regarding off-line identification and real time assessment of modelling uncertainty lag a long way behind techniques available in the research literature, and that the stochastic nature of Transfer Function models makes them a natural candidate for development of such approaches. However, there is also the widespread view that, whilst such assessments would be useful during a flood event, a forecast with a probability or range attached is difficult to interpret and would need careful structuring of flood warning procedures to avoid any misinterpretation. Guidance is required on sources of uncertainty (rainfall data, ratings, models etc) and approaches to assessment of uncertainty.

Issue 3.9: Another interpretation of Issue 3.8 is that traditional modelling and flood forecasting methodologies are yet to develop techniques for assessing the propagation (or cascading) of errors through the whole of the flood forecasting and warning processes (incorporating detection, forecasting, dissemination etc). As a result, it is often not possible to produce evidence that improvements in one part of whole system, say in flood forecasting, will ensure equal improvements in the final output (e.g. in flood warning performance).

3.3.4 System Environment

Issue 4.1: Although existing systems were 'state of the art' when they were implemented, System Environment issues are presently a major constraint on the future development of Transfer Function modelling within the Agency. For example, few of the current systems allow automated real time updating, the linking of models into integrated catchment models, or the use of Nimrod forecasts or Non Linear Transfer Function models. South West Region is presently taking a lead in this area with a number of improvements planned to the WRIP system in the next 1-2 years.

Issue 4.2: More generally, for the forthcoming NFFS, the mechanisms for third party modules to be attached to the system are still under development.

Issue 4.3: It is recognised that, even with existing systems, much could be done to assist direct use of forecast information by Flood Warning staff (e.g. by automated transfer of forecasts to telemetry systems), to improve training in interpretation of forecasts, and to formally incorporate the use of forecasts into existing Flood Warning Procedures.

3.3.5 Operational Applications

Issue 5.1: Whilst some Regions have a large number of calibrated Transfer Function models, many remain to be implemented operationally, and it is believed that there have been few instances of model outputs being used to issue Flood Warnings (in contrast to the situation with Conceptual and Flow Routing models, for example).

3.3.6 Operational Issues

Performance Monitoring

Issue 6.1: Performance Monitoring has recently gained a higher profile within the Agency as the means to identifying problems with existing models, and driving future improvements. Although the national "Real Time Modelling" guidelines (Environment Agency, 2002b) lay down generic advice on approaches to performance monitoring, this needs to include specific reference to Transfer Function models. In the shorter term, some generally agreed monitoring criteria are urgently required for national application.

Issue 6.2: Within the Agency, there is a persistent problem of a lack of confidence amongst Flood Warning staff (and some Flood Forecasting staff) as to the accuracy of Transfer Function models for real time flood forecasting applications. However, until recently, there has been insufficient performance monitoring upon which to base these suspicions and the true situation is much more complex than blanket statements that these models do not perform well (for example, it is likely that certain types of model work well in certain situations, or that perceived failings are more to do with inconsistent approaches to model calibration, catchment rainfall estimation and poor high flow ratings, rather than with the models themselves). However, it is noted that the use of national guidelines for "Real Time Modelling" together with the Agency's formalised modelling procedure (under development) offer a framework for learning from practice and improving the performance of the various modelling solutions.

Issue 6.3: To date, with the exception of R&D project W242 (which had a much wider scope), there appears to have been no attempt within the Agency to collate information on Transfer Function model performance at a national level or to draw conclusions on which models, procedures, systems etc work best in a given situation. However, there is a view that model intercomparison studies are difficult to perform on a truly level playing field and that the results can sometimes be controversial since model 'brand' names are often discussed, which poses the question of what other approaches might provide better information.

Quality Assurance

Issue 6.4: There is a view that approaches to Quality Assurance in model calibration and software development vary between Regions.

Issue 6.5: Guidance is required on the format and content required in model calibration and validation reports.

Technical Expertise

Issue 6.6: Within the Regions, there is a reasonable level of technical expertise in Transfer Function modelling, both in calibrating models and in developing improved methodologies. However, with the exception of the collaboration between North West and South West Regions, there is no national system in place for exchange of this information, resulting in a dilution of the Agency's capability in Transfer Function modelling.

Issue 6.7: Opportunities for Agency staff to work more closely with researchers should be identified e.g. exchange of data for case studies, Agency sponsored or supported MSc and PhD projects etc.

3.3.7 Future Development Plans

Issue 7.1: Current developments in Transfer Function modelling, and associated sytems, in some Regions, could be of benefit to other Regions, and opportunities for this transfer of expertise could be identified.

Issue 7.2: Notwithstanding the comments about model intercomparison studies (see Issue 6.3), there is a clear wish within the Agency for a study along these lines aimed at more advanced types of Transfer Function model than are used operationally at present.

Issue 7.3: Numerous areas for improvement (with appropriate guidelines) were identified by Agency staff during the consultations. The following recommendations from the Technical Report which accompanied the recently issued "Real Time Modelling" guidelines (Environment Agency, 2002b) provide a flavour of these proposals:

- Further investigation into the need for, and recommended types, of effective rainfall formulation under flood event conditions
- Developing generic approaches to updating, also using antecedent/current conditions and possibly 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.

4 TOWARDS BEST PRACTICE

This chapter summarises current knowledge regarding best practice use of Transfer Function models for flood forecasting applications. However, because the area of Transfer Function modelling is constantly evolving and, because there is only limited performance monitoring data available from operational applications, it is not currently possible to identify a single or best way of implementing these models. Precisely for these reasons, best practice is needed in terms of monitoring the performance of a model and improving it by increasing the information content of the model in a business-driven way. Despite these difficulties, a number of obvious improvements have been identified in the Agency's current use of Transfer Function models and these are summarised under the following general headings:

- Types of Models (Section 4.1)
- Real Time Updating (Section 4.2)
- Model Calibration and Validation (Section 4.3)
- Operational Issues (Section 4.4)

4.1 Approaches to categorising Transfer Function models

At present, the types of Transfer Function model which are potentially available to the Agency for flood forecasting applications are as indicated in Table 4.1:

Table 4.1 Some general types of Transfer Function model

General Type	Specific Type
Linear	Simple Linear
	PRTF variant
Non Linear	Linear with Effective Rainfall pre-processor
	Parallel Pathway
	Parallel Pathway with Effective Rainfall pre-processor

An additional aspect of model categorisation is whether the rainfall inputs should be lumped, semi distributed or fully distributed.

This review suggests throughout that at present there is insufficient performance monitoring data available to provide definitive guidelines on the most appropriate type of model to use in a given situation.

Perhaps the best general advice available is that offered in the recently issued national "Real Time Modelling" guidelines (Environment Agency, 2002b), which in turn was largely based on the general conclusions from the model intercomparison study W242 (Environment Agency, 2000). Adapted slightly to match the categories in Table 4.1, this general advice promotes the principle of "horses for courses" and is summarised in Table 4.2.

Table 4.2 Indicative Transfer Function modelling solutions (adapted from Environment Agency, 2002b)

Catchment Scale	General Type	Indicative Solution
Small Catchments	Upland impervious, frozen, rural or urban	Linear models
	Urban Clay	Simple lumped models may be acceptable but zoned or semi distributed conceptual models may perform better
Medium Catchments	High relief impervious	Most models perform well including Linear models
	High relief mixed geology	Non Linear models possibly with Parallel Pathways
	Lowland Permeable (chalk)	Groundwater dominated – either a Conceptual model or a Non Linear Parallel Pathway Transfer Function models with further development to incorporate real time borehole level data and pumped abstractions etc
	Modest Relief (rural)	Good performance can probably be obtained from simpler Linear models
	Modest Relief (significant urban)	Responsive so as above (although semi distributed models can help)
Large Catchments	Lowland Clay	Non Linear Parallel Pathway models
	Lowland Chalk	As for medium catchments (Lowland Permeable)

Catchment types can be discerned from hydrogeological maps, Flood Estimation Handbook statistics, and hydrological indicators such as the Base Flow Index.

However, regarding the division of catchment sizes into small, medium and large, there are no firm rules to follow, although the Flood Estimation Handbook recommends that, for off-line simulation models, semi distributed models are essential for catchment areas ≥ 500 km^2 (but are beneficial on smaller areas if the data can support this approach). Alternatively, hydrological or hydrodynamic routing methods should be used if possible.

More generally, both historical data and the FEH can provide a useful guide to the hydrological response of a catchment with respect to tributaries, soil, geology, topography etc and might be supplemented by Digital Terrain Model/GIS analyses in some situations. Also, the recently issued “Rainfall Measurement and Forecasting” guidelines (Environment Agency, 2002a) suggest a minimum raingauge spacing of 1 gauge per 100 km^2 for flood forecasting applications in frontal rainfall (with a closer spacing for thunderstorms and other less widespread events).

One other factor to consider is the influence of features in the catchment which may influence runoff response, and require modelling explicitly if a rainfall runoff model is to have any chance of success. Such features might include large lakes, reservoirs, snowmelt effects, areas of floodplain etc, and might point towards use of integrated catchment modelling solutions, combining rainfall runoff Transfer Function models with other types of model, such as reservoir models through to hydrodynamic routing models. The Agency's "Real Time Modelling" guidelines (Environment Agency, 2002b) give a detailed framework for consideration of the impact of such effects in the following situations:

- Fast response catchments
- Floods can occur on a permeable or dry catchment
- Flood response can vary depending on spatial variations in rainfall
- Groundwater influences
- Large lowland chalk or clay catchment
- Urban catchments
- Ungauged catchments
- Snowmelt Effects
- Routing issues
- Simple river reach
- Flat, lowland river
- Simple floodplain
- Embanked floodplain
- Levels only at reach ends
- Reservoirs
- Natural lakes, bogs and wetlands
- Mobile river bed
- Tributary inflows
- Fan shaped flow networks
- Flow Control Structures (sluices, barrages etc)
- Off line storage, abstractions, discharges and diversions
- Event specific problems

The Toolkit Approach

In the related field of Conceptual Rainfall Runoff modelling, it has long been recognised that, given the complexity of the rainfall runoff process, there is no 'one model fits all situations' approach. This has led in recent years to the development of modelling toolkits, which allow users to select from a range of sub-models to represent antecedent conditions, subsurface flows, runoff response etc, whilst providing an overall framework for model calibration and optimisation. A similar approach might usefully be adopted for Transfer Function modelling within the Agency, and 'Transfer Function Modelling Toolkits' of this type have already been produced in some research organisations for simulation modelling (although are not yet available commercially).

4.2 Key features of the main categories of model

Having taken the decision to use a given general type of model (see Table 4.1), there is then the question of which 'brand' of model to use within each class. Although this study specifically excluded discussion of model 'brands', it is worth noting that the situation in the UK (early-2004) is that there is currently no generally available ('shrink wrapped' or 'packaged') commercially available model calibration and optimisation package for Transfer Function models, and that the remaining university-based techniques often come in several 'flavours', reflecting a continuous process of improvement as new research ideas are developed.

Table 4.3 attempts to summarise some generic conclusions regarding model types based on the consultations performed during this project:

Table 4.3 Main Considerations regarding model types from consultations (+ = benefit of this type, - = possible disadvantage)

Type	Main Considerations from Consultations
Simple Linear	+ Can result in low order, parsimonious models - Possibility of instabilities or oscillations
PRTF variant	+ Output constrained to be positive and non oscillatory - May increase the number of parameters to calibrate
Linear with Effective Rainfall pre-processor	+ Simpler to calibrate than a parallel pathway model - May not fully represent sub-surface flow contributions
Parallel Pathway	+ No requirement to calibrate effective rainfall component - Does not fully represent catchment antecedent conditions
Parallel Pathway with Effective Rainfall pre-processor	+ Most complex type at present providing best chance of representing large, permeable catchments - Can require considerable expertise to calibrate

Regarding effective rainfall estimation, for the methods discussed in Section 3.1 the main considerations are presented in Table 4.4:

Table 4.4 Some considerations concerning the effective rainfall formulations discussed in Section 3.1

Method	Main Considerations from Consultations
Soil Moisture Accounting	+ Long and successful track record in the UK and overseas - Conceptual formulation moves away from the purely data-based approach
State Dependent Parameter	+ Data readily available in real time - Concept of effective rainfall depending on flow is sound but at first sight counterintuitive
Constant or Variable Loss	+ Simple to implement and based on the FEH approach - Questions over validity for real time use

4.3 Real Time Updating

For flood forecasting applications, the possibility of real time updating of forecasts provides a key opportunity for improved forecast accuracy compared with results obtained using off-line (simulation) modelling.

Although automated updating is routinely used for some other types of model within the Agency (e.g. flow routing models, conceptual rainfall runoff models), most updating of Transfer Function models is currently performed manually. However, the EPSRC Consortium of Flood Risk Management has identified Flood Forecasting and Warning as one of its research Priority Areas with a task on developing generic updating modules, directly attachable to the NFFS. Also, South West Region has commissioned a study (reporting in 2004) to evaluate several types of updating scheme for possible implementation on WRIP

The Agency's "Real Time Modelling" guidelines (Environment Agency, 2002b) note that, in recommending appropriate updating schemes, a particular difficulty can be that the procedures used are often closely linked to the particular 'brand' of model, and cannot be discussed in isolation from the model. Since a discussion of 'brands' is outside the scope of this study, this presents a particular problem in providing general guidance.

However, for Transfer Function modelling, the situation is slightly different in that many of the methods proposed are generic (see Table 2.3), and a preliminary assessment of the suitability of methods for Agency use is presented in the Table 4.5.

Table 4.5 Preliminary assessment of the suitability of real time updating schemes for Agency application for Transfer Function modelling

General Category	Type / Name	Suitability for Agency application
Error prediction	Graphical Correction	In effect the method used at present in Southern Region (and possibly elsewhere)
	Time Series Model+	No known Agency applications although should be suitable for any type of model provided that the differences between model output and observed flows are not purely random.
	Pattern Matching	Not used at present but many similarities with the manual parameter tuning method used in the South West and North West Regions
State updating	Flow Substitution+	Recently evaluated for possible use in South West and North West Regions; simple to implement.
	Adaptive Gain	An early technique for tuning models based on adjustments to a single variable – probably now superseded by better methods
	Kalman Filtering	No known operational applications to date within the Agency
Parameter updating	PRTF approach	Currently performed manually in South West and North West Regions (in North West 'by eye' and in South West by pre-prepared look up tables relating the tuning parameters to Catchment Wetness Index).
	Transfer Function Noise	
	Time Varying Parameter (TVP)	Could also be used
	Genetic Algorithm+	No known operational applications to date within the Agency

\+ Currently under evaluation in South West Region (2003-04)

In principle then, any of these methods could be used but there is little performance monitoring data available to assess the most suitable approach; however, the EPSRC and South West Region studies referred to earlier should soon provide better guidance on the most appropriate schemes to use for a given situation.

It is also perhaps worth highlighting a few general principles of updating which – if ignored – can show individual updating schemes in a bad light (Table 4.6).

Table 4.6 Generic guidance on application of real time updating schemes to Transfer Function models

Issue	Description
Model Structure	Real time updating is not expected to compensate for a poorly structured model (see Section 4.1). At the very least, the general magnitude and timing of the peak should be correct.
Input Data	Real time updating cannot always compensate for the errors inherent in input data (spikes, drop outs etc) and Transfer Function models – being event based – are vulnerable to this effect. Some form of quality control (max, min, max change) or filtering of input data is therefore desirable.
	One particular situation where updating may fail is when using flow estimates where the rating is non unique or levels vary little with increasing flows (e.g. due to backwater effects, floodplain influences, fluvial/tidal influences, non modular flows at structures).
	If the flow 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.
	Particular care is required when using updating in situations where the flow can be influenced by structure operations since there is a risk that the updating model may give rise to complex feedback effects requiring further investigation.
Model Output	Ideally the real time software used should allow Flood Forecasters to make comparisons of the adjusted and original forecasts to help spot situations when the updating routines may not be operating as expected.

4.4 Model Calibration and Validation

Model calibration is central to the successful use of any type of model and was identified as a key issue from the consultations. The factors which need to be considered include:

- Calibration Criteria
- Automated Optimisation Procedures
- Calibration for Real Time Use
- Data Issues

Although, as in most other areas of Transfer Function modelling, there are alternative views on the best approach to take in some of these areas, some general principles can be identified and are described in the following subsections.

Some general principles

The “Real Time Modelling” guidelines also provide some general principles for model calibration under the following headings.

- Use the same sources of input data which will be used in real time operation
- Focus the calibration on the aspects of model performance required in real time
- Use calibration events representative of major events under current conditions (catchment, flood defences, instrumentatione etc)
- Double check data for large flood events
- Understand and document the limitations of the model
- Assess the sensitivity and stability of the model to parameters and data
- Optimise model performance for the run time environment
- Use an appropriate level of quality assurance for model development

These guidelines should be referred to in addition to the information contained in the present section.

4.4.1 Calibration Criteria

For flood forecasting applications, a number of aspects of the model behaviour are of interest including:

- The magnitude and timing of the peak
- The time(s) at which critical thresholds are passed (e.g. Flood Warning or Severe Flood Warning levels)
- The volume under the hydrograph above a threshold (for estimating flood spills) and the time spent above that threshold
- The time at which levels or flows drop below a critical threshold (for issuing an All Clear)

In modelling terms, these considerations suggest that ideally a flood forecasting model should be optimised on the shape and timing of the full hydrograph above a threshold, ideally defining the choice of thresholds using a risk based approach dependent on the impact and probability of flooding.

In practice, the majority of studies in the Agency to date have chosen the magnitude and, sometimes, the timing of the peak, and the shape of the full hydrograph from the time that flows start to rise (usually expressed as the R^2 coefficient or root mean square error), and all of these measures provide a reasonable guide to the information actually required for flood forecasting.

The one exception is perhaps the need for high accuracy on the rising limb of the hydrograph as levels approach Flood Warning or Severe Flood Warning thresholds, and this criterion could perhaps be added to those which are already in use. Also, when computing R^2 values, it might be beneficial to also compute values for flows above a threshold, rather than for the full hydrograph.

A contingency table approach can also highlight the success of the model in predicting the crossing of thresholds; for example the Probability of Detection (PoD), False Alarm Rate (FAR) and Critical Success Index (CSI). These measures are defined in Section B whilst Figure 4.1 attempts to illustrate the relative magnitudes of these various criteria when trying to reproduce different aspects of the flow response (in particular how a simple timing error can have a disproportionately large impact on some calibration statistics whilst hardly affecting others). In the figure, the high and low scores relate to the value of the criterion, where applicable, within its permitted range (for example, the CSI, POD, and FAR measures are constrained to lie within the range 0 to 1, whilst peak level errors have – in principle – no limits on their magnitude).

The "Real Time Modelling" guidelines and associated technical report also provide an in-depth discussion of alternative model calibration criteria should this be required.

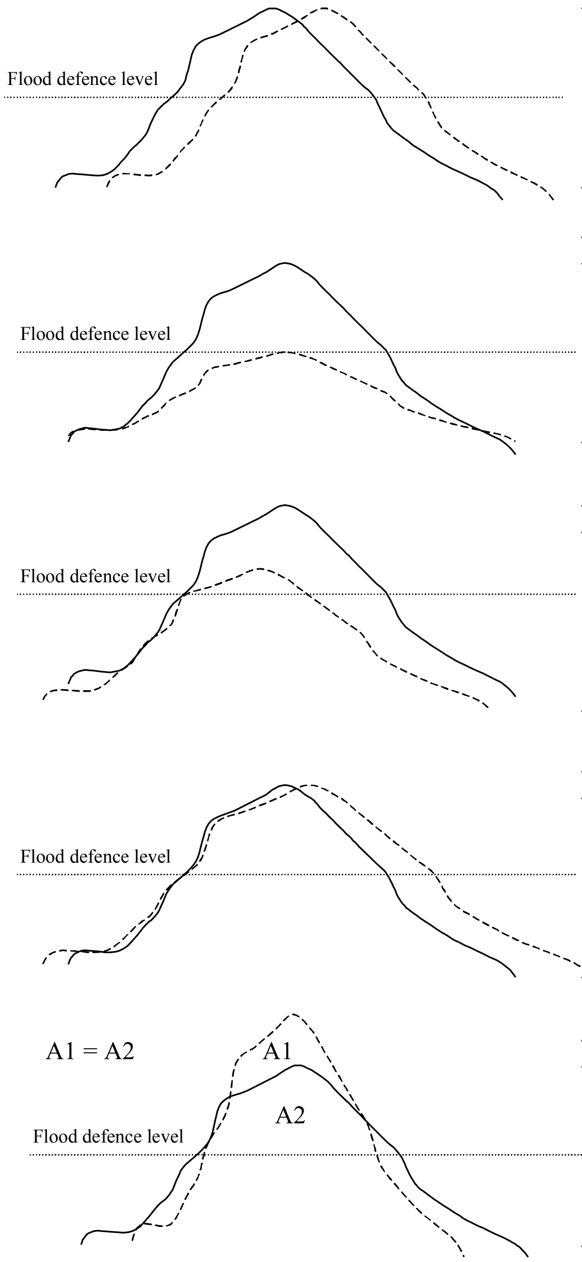
4.4.2 Optimisation Procedures

Optimisation procedures attempt to guide the model user both towards an appropriate model structure and the optimum parameters for that structure, given the calibration criteria which have been selected.

In the research literature, a number of optimisation techniques are proposed and have various advantages and disadvantages as outlined in Section 2.4. However, in current Agency practice, the precise optimisation technique used is not critical, since these techniques are used primarily as an initial guide to parameters, with the final optimisation usually being performed manually according to the selected calibration criteria and consideration of the impulse response.

One other aspect of optimisation is the order of model selected. Table 3.4 suggests that there can be wide variations across the Agency with no firm view amongst researchers as to the optimum order, except for the following general points:

- The fewer parameters the better is a widespread view (with model orders of (2,2,T) or less sometimes proposed as optimum)
- Use of a pure time delay can reduce the number of parameters required further and indicative values can be estimated from typical catchment response times
- More parameters are required for shorter time steps



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 3.3. Examples of performance measures for fixed lead time forecasts

—— Observed levels ----- Forecast levels (L = low, H = high)

Figure 4.1. Examples of Performance Measures for Fixed Lead-Time Forecasts (Environment Agency, 2002b)

(Solid line – observed levels, Dashed line – forecast levels; L=Low, H=high)

Regarding the model time step, for flood forecasting applications it is clearly desirable to achieve good resolution of changes in flows on the rising limb of the hydrograph. For example, for a river which typically rises from moderate to flood flows in 3 hours, say, then an hourly time step would only give 3 data points, whilst a 15 minute time step would give 12 data points. As another example, for the related area of unit hydrograph modelling, the Flood Studies Report (FSSR16) recommends a time interval of 1/5 of the catchment time to peak (rounded to the nearest whole number).

An indicative target of 5-10 data points on the rising limb of the hydrograph seems reasonable, suggesting that for fast response rivers a model interval of maybe 15-30 minutes is most appropriate. However, for slower responding rivers, an hourly time step might produce models with fewer parameters. It is recommended that sensitivity studies are performed where appropriate.

More Advanced Considerations

These recommendations only touch upon some basic fundamentals of model calibration, and amongst researchers there is considerable debate about the merits of different automated optimisation techniques, the structures of models which are produced, the possible adoption of continuous time formulations, and the effectiveness in reducing the cross correlation and autocorrelation remaining in the model residuals following calibrations. These issues are discussed in more detail in Section B of this report.

4.4.3 Calibration for Real Time Use

Compared to calibration for off line simulation of flows, real time models additionally may have updating routines included, and additional calibration statistics can be calculated for differing forecast lead times. There may therefore be benefits in calibrating models with a given lead time in mind, and optimising the performance with the updating routines in operation (e.g. Reed, 1984; Young and Tomlin, 2000; Environment Agency, 2002b).

This calibration for a purpose (in this case flood forecasting) seems intuitively sound and indeed was recommended in the “Real Time Modelling” guidelines. However, at present, all Agency Transfer Function models are calibrated in off-line mode although sometimes with the updating model in place.

One way to calibrate for a given lead time is via fixed lead time forecasts, which are the ‘pseudo hydrographs’ constructed by interpolating between the forecasts at the required lead time (e.g. 1 hour ahead) at each time step in the simulation. The model performance against chosen calibration criteria can then be assessed in the usual way (e.g. as illustrated in Figure 4.1).

Following on from this approach, if the model forms one component of a wider model (e.g. an integrated catchment model), the performance of the overall network of models should also be investigated, having first checked that the performance of the individual models within that network are satisfactory. The inherent notion is related to the cascading of errors from one component to another; an area which has been largely overlooked in most research studies to date. One of the reasons for this is that models are often brought together at different resolutions without defining a clear interface between each component. The absence of interfaces from modelling is often dictated by software architecture and this should be recognised as an important barrier to improvement. An opportunity will be created by the NFFS to remove these barriers and create a new capability to study the cascading of errors among integrated models.

4.4.4 Data Issues

Data issues are of key importance to model calibration and include such questions as:

- What types of input data should be used ?
- How many events are required for model calibration and validation ?
- Can model outputs be extrapolated outside the range of calibration data ?
- How can model uncertainty and accuracy be assessed ?

These and related questions are discussed in the following subsections.

Input Data

The main types of input data to a Transfer Function model are the observed or forecast rainfall, flow at the start of the event, and flows during the event (if certain types of real time updating are used). Secondary parameters, such as air temperature, may also be required for effective rainfall estimation.

Perhaps the main recommendation is that models should be operated in real time on the same sources of data used in model calibration. Hence, if a model was calibrated on raingauge data, then that same set of raingauges, with the same catchment averaging procedures, should be used in real time. This is particularly the case if weather radar based measurements or forecasts of rainfall are to be used, since there may be significant systematic (and random) differences between raingauge and radar based estimates of rainfall for a catchment

If raingauge data are used, then possible methods for computing catchment average rainfall include:

- Simple averaging
- Fixed weights (e.g. Thiessen polygons)
- Variable weights
- Surface fitting
- Geostatistical methods

The recently issued “Rainfall Measurement and Forecasting” guidelines (Environment Agency, 2002a) give advice on the various strengths and weaknesses of these approaches, together with information on weather radar data and Met Office rainfall forecast products e.g. Nimrod.

Which is better – radar or raingauges ?

A frequently asked question is whether radar or raingauge based estimates of rainfall are more suitable for use with rainfall runoff models. This is another classic case where the principle of 'horses for courses' applies and the answer depends on many factors, including raingauge spacing, raingauge elevations, distance from the nearest radar, local topography, catchment averaging procedures, and the type of event being considered (frontal, convective). Site specific studies are required to determine the accuracy of the proposed approach for the application, combined with routine post event analysis. Also, for the future, the Met Office is seeking to integrate radar and raingauge data more closely through the Rainfall Collaboration Project.

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For flow data, estimates may be derived directly (e.g. from an ultrasonic recorder), implicitly (e.g. via a theoretical rating for a structure) or indirectly (e.g. from measured levels using a rating curve). In all cases, it is important to evaluate the accuracy of measurements at the highest flows used in the model calibration and validation, to be sure that the model calibration is not affected by poor data. Also, the influence of backwater, tidal and other effects should also be taken into account.

Where rating curves are used, due to a lack of spot gaugings, it is often necessary to extend the rating to high flows, and a variety of methods are available as reported upon in the R&D project "Extension of rating curves at gauging stations W6/060". Sensitivity tests might also be performed using different flow estimates computed using confidence limits on the rating curve.

It is also generally recommended that – for both model calibration and real time operation – flows are expressed in the same units as rainfall (typically mm per time interval) since this provides flow and rainfall parameters of a similar magnitude (so that rounding errors are not a concern, for example). Also, derived parameters such as the steady state gain have an immediate physical interpretation (as a pseudo runoff coefficient).

A rainfall-level model ?

One other possibility, which has been explored in North West Region, is to calibrate Transfer Function models directly to river levels. Although this method is little reported in the literature, there seems no major theoretical reason not to do this, provided that the relationship between levels and flows is unique and that levels continue to increase with increasing flows (i.e. no backwater, floodplain or similar effects. Indeed, a more sophisticated version of this approach is already used for some conceptual rainfall runoff models, where the rating is jointly calibrated with the model parameters. However, further investigation is required to assess the suitability of this approach. Also, it is worth noting that the 'physical' interpretation of the steady state gain as a runoff coefficient would no longer be valid with this approach, and – depending on the relative magnitudes of flows and levels – there might be some mismatch in the magnitudes in the a and b parameters of the model (as defined in Equation 2.1)

Calibration and Validation Events

Transfer Function rainfall runoff models are normally calibrated on an event basis i.e. using only data for flood events (the calibration or 'training' datasets). For this type of model, the "Real Time Modelling" guidelines recommend that at least 5-10 events are required for calibration, using the same time step and sources of data as will be used in real time. Ideally, validation tests will then be performed using a similar number of events (which were excluded from the original calibration).

As pointed out in the "Real Time Modelling" guidelines, 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 applications, 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. Ideally, the calibration dataset will include a range of the types of events which the model is to represent e.g. short duration high intensity rainfall, long duration moderate intensity rainfall.

To derive the optimum set of parameters across all of the calibration events, some possible strategies are outlined in Table 4.7.

Table 4.7 – Some possible approaches to model calibration on multiple events

Approach	Recommendation
Optimise for largest event	Possibly a valid approach if confident in the high flow data and the model is verified against a number of other events. For example, might be used if calibration dataset contains only small to moderate events.
Optimise across all events	The usual approach used in the Agency and elsewhere – valid if the calibration dataset contains at least one event of the required magnitude (e.g. flood warning level)
Average parameters across all events	Theoretically unsound and not recommended
In-bank saturated event	Again, a valid approach if a suitable event (or events) can be identified and the resulting model is verified or further refined against more events (particularly larger events and events on dry catchments). For example, this approach might be used where there are uncertainties in high flow ratings and it is thought that flooding is most likely to result from a saturated catchment.

The justification for use of an in-bank saturated event is that – even if this is only a moderate event – at least the rating curve (if used) should be well defined, and the issue of effective rainfall estimation does not need to be considered.

When optimising across all the calibration events, the question arises of whether to perform the analysis for each event singly, or to concatenate the events to form a single time series. There is no consensus on the best approach to take, although if concatenation is used then care is needed to avoid unrealistic step changes in flows between events, or spurious autocorrelations arising between events which are separated in time. One possible solution is to substitute a long run (several days or more) of dummy values between events, set to a constant value (e.g. the mean). An important point to note about these various stategies is that – although each is a reasonable approach – the outcomes may differ. Therefore careful documentation of the model calibration process is required to assist in maintaining the integrity of a model over time.

Extrapolation of Model Output

A consideration for all types of model is the extent to which model outputs can be trusted when using data outside the range of the model calibration. This is particularly relevant for flood forecasting applications, where it would be hoped that, when a huge event occurs, the model provides at least a guide to the likelihood of flooding.

For sophisticated physically based models, such as hydrodynamic models, extrapolation can often be performed with some confidence. However, for purely data-based models, such as Transfer Function models, the issue of extrapolation is more problematic and, for the simpler linear types of model, it might be argued that this goes against the basic concept of this type of model, which is to provide a relationship between known inputs (rainfall) and known outputs (flow), and nothing more.

However, common sense suggests that extrapolation of output is most likely to be successful in the following situations:

- No step changes in flow response occur beyond those events used in the calibration dataset (e.g. flows going out of bank, structures being bypassed, backwater influences from downstream tributaries)
- No step changes in the catchment configuration (e.g. different reservoirs or tributaries influence flood flows beyond a given threshold)
- The model has some physical basis (e.g. Non Linear and/or Parallel Pathway models) and its stability is ensured for all inputs (e.g. PRTF models)
- Real time updating on flows is being used, so that the observed flows guide the model output (at least at short forecasting lead times)
- The extreme flows are due to a rainfall event of a type which appeared in the original calibration dataset (e.g. thunderstorm, frontal, orographic)

Some testing of the model response to extreme events can also be performed during model development by using synthetic rainfall events e.g. summer 50% or winter 75% profile storms of different depth durations more extreme than those observed to date.

Assessing Model Uncertainty

For any model, there will always be some residual uncertainty arising from errors in input data, the calibration process and other factors. As noted in Section 3, current Agency procedures regarding off-line identification and real time assessment of modelling uncertainty lag a long way behind techniques available in the research literature, and the stochastic nature of Transfer Function models makes them a natural candidate for development of such approaches.

Probably the most sophisticated approach is to generate stochastic realisations of rainfall inputs, combined with estimates for parameter uncertainty, to derive probability distributions for flow outputs, and Section B provides a detailed discussion of these and other methods for assessing uncertainty in Transfer Function models.

However, a number of simpler methods might also be used which include:

- Sensitivity test to different types of data input (radar, raingauge, Nimrod etc)
- Comparisons of model output for different model structures
- Comparisons of model output with and without updating, and for different updating methods
- Comparisons of models using total rainfall and effective rainfall formulations
- Analyses using flow sequences computed using different rating equations (e.g. within confidence limits as proposed earlier)

The main focus of these simpler methods is to assess the robustness of the model to different model and data assumptions, rather than quantifying uncertainty (and – at present – no Agency Region has software capable of estimating and displaying uncertainty in real time).

4.5 Operational Issues

4.5.1 Performance Monitoring

The "Real Time Modelling" guidelines note that, like most of the Agency's other assets (instruments, flood defences etc), Flood Forecasting Models require regular reviews of performance and occasional recalibration to maintain optimum performance. In addition to initial monitoring following calibration, some factors which can cause model performance to deteriorate over time include:

- Changes to calibration data inputs (ratings, raingauges, radar etc)
- Catchment and floodplain developments (flood defences, dredging etc)
- Impact of large flood events (damage to instrumentation, scouring etc)
- Variations in the magnitude of measurement errors
- New versions of models (new versions, bug fixes etc)

and one focus of performance monitoring should be on identifying the causes of problems and remedying them.

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 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. Alternatively, the generic modelling framework discussed in Section 2.4 will put in place the development of information resources (databanks etc) which will underpin a need-driven process for refining the modelling solution.

Some possible approaches to model performance assessment include:

- Contingency tables showing the success at forecasting Flood Warnings and Severe Flood Warnings
- Fixed lead time values for the R^2 statistic and Critical Success Index (CSI) vs lead time, peak magnitude and timing errors vs flow, standard deviation of the estimates (e.g. accuracy ellipses)

These and other suggested measures are described in more detail in the "Real Time Modelling" guidelines. The following tables also show examples of performance summaries from the technical report issued with those guidelines.

Table 4.8(a) Suggested format for summarising forecast warning time performance

Reach and type of warning		**Minimum warning time achieved**						
		After start of flood	< 2 hrs	2-4 hrs	4-6 hrs	6+ hrs	Modal value (hrs)	Target (hrs)
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	

FW = Flood Warning, SFW = Severe Flood Warning

Table 4.8(b) 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	SFW	0	0	0	0	0.57
Lilbourne	FW	1	**8**	3	12	
	None	0	2	-	-	
A2	SFW	0	0	0	0	0.25
Rugby	FW	0	**1**	0	1	
	None	0	3	-	-	
A3	SFW	**1**	0	0	1	0.67
Warwick	FW	0	**1**	1	2	
	None	0	0	-	-	
A4	SFW	0	0	0	0	1.00
Stratford	FW	0	2	0	2	
	None	0	0	-	-	

FW = Flood Warning, SFW = Severe Flood Warning

In Table 4.8(a), the table shows the number of events within each category, and the modal value is the median across all events. In Table 4.8(b), again the number of events meeting all criteria are shown, together with the Critical Success Index, defined as the number of successful warnings (shown in bold) divided by the sum of all the entries for the reach excluding the 'no warning'+'none' combination. A format of this type has recently been adopted in South West Region and an example is shown in Appendix A1.

Some additional points to note in performance monitoring are:

- Normalised values should be used for comparisons between sites (e.g. peak flows related to the mean flow or 100 year flood, or non dimensional measures such as CSI or R^2)
- 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

4.5.2 Quality Assurance

Quality Assurance is essential to the calibration and maintenance of models and can be performed at two levels:

- By following good practice in calibration, implementation and documentation of models and the software that they use
- As above, but within a recognised British Standard or ISO framework

From the brief surveys performed during this project, most current Transfer Function modelling within the Agency falls into the first of these categories. However, the basic principles of quality assurance are the same in all cases, and typically consist of:

- 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

Reports by HR Wallingford (Seed et al, 1993), Environment Agency (1998a) and Environment Agency (2002c) give a good indication of the types of procedure which should be followed.

5 CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed the current use of Transfer Function models within the Environment Agency, and the latest research developments in this area. These studies have confirmed that Transfer Function models can provide a robust, fast and accurate approach to flood forecasting providing that models are applied within their calibration range, and that users have a good understanding of the assumptions and limitations of the approach. Results can also sometimes be extended to higher flows where models incorporate some notion of catchment response (e.g. parallel pathway models, or models using an effective rainfall preprocessor) and/or use real time updating.

However, following the review and consultation work performed as part of this study, a number of areas have been identified for improvements in the current application of Transfer Function models within the Environment Agency. This section summarises the main conclusions in the areas of operational improvements and requirements for future research and development, and is presented in the same order of section headings used earlier in the review of issues (Section 3.3).

One particular problem identified throughout is the need for improved software for real time use so – where a recommendation involves the development of additional software – this is highlighted by an [S] symbol following the text. Also, areas for future research are indicated in italics.

5.1 Types of Model

- Transfer Function modelling is an internationally recognised approach to flood forecasting but, at present, the Agency only uses a small fraction of the types of Transfer Function model available. The Agency should therefore consider making wider use of the tools available in order to fully exploit this modelling approach. Individual Regions will also need to commission improvements to existing models (or new types of model) for implementation on existing systems where the NFFS is not yet available, and an Agency-wide strategy is required for development of Transfer Function Forecasting Modules for implementation on the NFFS [S]

- At present, all Agency applications of Transfer Function models are as 'stand-alone' models, rather than integrated into catchment models. The NFFS – when delivered – will facilitate the development of integrated models but shorter term improvements might also be considered in Regions where the NFFS is not yet available [S]

- Within the Agency, there is a strong demand for a guideline and quality control document specifically for Transfer Function modelling. This should cover recommended approaches to selection of the appropriate type of model, calibrating the main categories of Transfer Function model, and include checklists for use in documenting the calibration and validation process as well as worked examples illustrating application of the methodology. Following a period of operational use and evaluation, this document could form the basis for the development of formal Quality Assurance procedures by the Agency in future years. Alternatively, the Agency may incorporate or adapt the tools currently being developed on the ongoing European Union funded HarmoniQuA research project.

- Several methods have been reviewed for allowing for the impact of catchment antecedent conditions on model forecasts and – at present – it is not possible to say which methods work best in a given situation. *This situation is not likely to change in the near future but further investigation and evaluation could help to apply the principle of 'horses for courses' for existing methods and in building up a knowledge base to help guide future development of these techniques.*

- *The modelling 'toolkit' approach, currently being developed by a number of researchers, could possibly be extended to Agency use of Transfer Function models in the form of well-documented, quality assured, user friendly, NFFS-compliant software, so that practitioners have the flexibility to evaluate a number of possible model types, calibration approaches and optimisation criteria etc as part of the model development process* [S].

5.2 Real Time Updating

- At present, no Agency Region uses automated updating of forecasts from Transfer Function models and this is a priority for future development. The outcomes of the updating components of the current South West Region feasibility study, and EPSRC Flood Risk Consortium, should be evaluated at the earliest opportunity and the best practice results fed into operational practice [S].

- At present, most Agency Transfer Function models are calibrated in simulation mode, but for the future there may be advantages from optimising model performance for the required lead time e.g. as specified in high level targets, and possibly operating a suite of models simultaneously in real time, each optimised according to different lead time criteria [S].

- Since Transfer Function models are event based, they can be vulnerable to short term drop-outs or spikes in data. Where this is not performed already, filtering and infilling techniques should be used to safeguard against this possibility in operational systems [S].

5.3 Model Calibration and Validation

- This report lists a number of approaches to model optimisation but as yet there is insufficient performance monitoring data to definitively recommend any one approach. *The situation is likely to remain unchanged for the near future but further monitoring and evaluation is required, together with evaluation of more sophisticated calibration criteria (e.g. threshold crossing, contingency measures)* [S].

- All Regions have the option of using either weather radar or raingauge rainfall inputs to drive Transfer Function models, and it is important that a model is operated in real time on the same type of data as used for calibration. The recently developed South West Region idea of displaying forecasts from both radar and raingauges might be adopted in other Regions. *Also, the real time use and evaluation of Nimrod short term forecasts (say up to 3 hours ahead) should be considered to extend the lead times on fast response catchments* [S]

- A common problem in all flood forecasting model development is uncertainty in the high flow ends of rating curves and extrapolation of model output. The proposed guideline document (see Section 5.1) could provide proposed methodologies for addressing these issues including recommendations based on the outputs from a recent Agency R&D project "Extension of rating curves at gauging stations W6/060". *The use of rainfall-level forecasting models might also be investigated further.*

- It is generally agreed that current Agency procedures regarding off-line identification and real time assessment of modelling uncertainty lag a long way behind techniques available in the research literature, and that the stochastic nature of Transfer Function models makes them a natural candidate for development of such approaches. The proposed guideline document (see Section 5.1) could summarise current knowledge regarding sources of uncertainty (rainfall data, ratings, models etc) and approaches to assessment of uncertainty although – since this is an active research area – definitive approaches cannot be recommended at present.

- *For the future, a possible route to improving the Agency's approach to modelling uncertainty might initially start with developing suitable software and techniques for estimating uncertainty off-line (e.g. variance, confidence limits), the display of those estimates in real time together with the forecast values, training of operational staff in interpretation of these estimates, and designing ways of building these techniques into operational flood warning procedures. In the longer term, stochastic sampling of rainfall data and forecasts, and model parameters, might be performed in real time, with key statistics displayed to operators (e.g. confidence limits, medians, distributions); also, ensemble rainfall forecasts might become available to the Agency from the Met Office and used in real time to drive models (the number of runs per time step might be of the order 1000-10000, and 10-100 respectively with current technology)* [S]

5.4 System Environment

- System Environment issues are currently a major constraint on the implementation of new or upgraded forecasting models. In the long term, decisions need to be taken on the types of Transfer Function model to implement on the NFFS (and Forecasting Module development commissioned), whilst in the shorter term – before delivery of the NFFS - each Region needs to decide on the improvements required to existing systems [S]

5.5 Operational Applications

- For Transfer Function models, there is a general problem within the Agency that forecasting model outputs are not fully integrated into operational flood warning procedures; for example, the inclusion of forecast trigger levels in procedures as well as the usual triggers based on observed values. Possible improvements include the automated transfer of forecasts to telemetry systems so that they can be viewed alongside the telemetered data, improved training in forecasting techniques for operational staff, and making forecasts more readily available in Area incident rooms by other means (e.g. email, fax, or remote access to the forecasting system).

5.6 Operational Issues

5.6.1 Performance Monitoring

- Performance monitoring of forecasting models is recognised as a high priority within the Agency and this report summarises a number of possible approaches for the case of Transfer

Function models. The proposed guideline document (see Section 5.1) could present worked examples for a number of case studies, and propose a range of approaches for operational use. *Automated approaches to performance monitoring should also be developed* [S]

5.6.2 Quality Assurance

- At present, there are wide variations in the degree of quality control applied to the development of Transfer Function models. Although quality control guidelines are available within the Agency for hydrodynamic models, there appears to be no comparable document for Transfer Function models, and this could possibly be developed as part of the guideline document discussed in Section 5.1. In the longer term, the Agency should work towards full British Standard accredited QA procedures for model development, and the proposed quality control manual could form a starting point in this process.

5.6.3 Technical Expertise

- Within the Agency, there is considerable expertise in Transfer Function modelling, and the current informal collaboration between South West and North West Regions could possibly be extended to include sharing of information between Regions (e.g. documentation), regular meetings with representatives from all Regions with an interest in rainfall runoff modelling (and possibly universities and consultants). A regular newsletter (by email or paper copies) might also help in disseminating information, together with pages on the Agency's intranet.

- More generally, there are many misconceptions within the Agency about the usefulness and performance of Transfer Function models, and sometimes of the underlying theory. Regular training courses for key practitioners, including sessions from invited experts, might help in solving some of these problems, and highlighting some of their advantages (robustness, event-based, fast and simple to run etc).

- Opportunities for Agency staff to work more closely with researchers should be identified e.g. exchange of data for case studies, Agency sponsored or supported MSc and PhD projects etc.

5.7 Future Development Plans

Numerous areas for future research were identified during the review and consultations including:

- *Further investigation into the need for, and recommended types, of effective rainfall formulation under flood event conditions*

- *Further intercomparison studies between types of Transfer Function model*

- *Developing generic approaches to updating, also using antecedent/current conditions and possibly smoothed versions of the observed flows*

- *Evaluation and use of new model structures (more parsimonious, parallel pathway etc)*

- *Investigation of appropriate model calibration criteria for flood forecasting applications (rising limb measures, values over threshold etc)*

- *Further evaluation of the use of radar-based rainfall actuals and Nimrod forecasts*

- *Choice of appropriate timesteps to fully resolve the rising limb of the hydrograph and use of continuous-time formulations to overcome some of the issues associated with the choice of model timestep*

- *Further investigation into ways of assessing the impacts of model and data uncertainty on forecasts both off-line and in real time*

- *Investigation of the performance of models when extrapolated outside their calibration range (e.g. for large floods) and of appropriate calibration approaches to optimise behaviour in these conditions*

- *Investigation of the possible use of the MOSES product for characterisation of antecedent conditions*

- *Further investigation of other forecasting applications of Transfer Function models e.g. flow routing, estuary forecasting, rainfall-level forecasting*

- *Development of risk based forecasting and performance measures, appropriate to the level of flood risk and available resources*

These topics, and those listed in previous sections, should be fed into the ongoing EPSRC Flooding Consortium research plans, and additional Agency sponsored R&D commissioned as necessary.

Section B – Technical Issues

6 RECENT TECHNICAL DEVELOPMENTS

The aim of this chapter is to take a more in depth look at the technical background to Transfer Function models, and at recent research developments which have not yet transferred to operational use. The mathematical content, and detail provided, is therefore greater in Section A of the report.

The chapter begins (Section 6.1) with a general review of the history of Transfer Function modelling, before proceeding in Section 6.2 to a more in-depth review of some specific categories of model. Section 6.3 then discusses approaches to real time updating of Transfer Function models.

6.1 Introduction

Before discussing some specific categories of Transfer Function model (see Section 6.2), it is perhaps useful to provide a general overview of the historical development of this type of model, and of current research activity in this area.

For flood forecasting applications, much of the early work on Transfer Function began in the 1960s and continued into the 1970s, in part prompted by publication of the still widely quoted textbook by Box and Jenkins (1970). Other types of model which appeared in the time series analysis and systems control literature at that time included the ARMA, ARMAX and DARX-type models, although there appear to have been few hydrological applications of this class of model (see Lees, 2000; Toth *et al.*, 2000 for examples).

In this period, a number of systems engineers, and classically trained hydrologists, identified the possible applications of time series models to rainfall runoff models, and the best ideas concerning model structure and calibration were adapted for use in flood forecasting applications. Table 6.1 summarises some early hydrological applications of time series analysis techniques including the Transfer Function modelling approach from that time.

This list, whilst not comprehensive, provides an indication of the types of model which were considered in the early days of research in this area. Research groups who were active in this area at that time include the University of Lancaster, the Institute of Hydrology, and the University of Birmingham.

Table 6.1 Some early applications of transfer function models in hydrology in the UK

Reference	Type	Updating	Application
Nash (1959)	Linear Model	None	Introduces the concept of a series of linear reservoirs for flow routing in a catchment (the 'Nash Cascade') which has a Transfer Function modelling interpretation
Young (1974)	Linear Model	Time Varying Parameter	
Whitehead and Young (1975)	Effective Rainfall plus Linear Model	None	Water quality model of the Bedford Ouse river in Anglian Region
Moore, R.J., O'Connell, P.E.. (1978); Moore, R.J. (1980)	Linear Model	Transfer Function Noise	Evaluation on several British catchments
Biggs (1980)	Effective Rainfall plus Linear Model	Flow Substitution	Flood Forecasting system for the Somerset Division of Wessex Water Authority

It is probably fair to say that, following this initial great interest in Transfer Function models (for flood forecasting), research activity then tailed off again until the late 1980s/early 1990s. The impetus for this new work included development of the WRIP system environment (for what are now North West and South West Regions), development of the IHACRES modelling approach and software at the Institute of Hydrology (now CEH Wallingford), and continued research into the DBM form of model at the University of Lancaster:

- The WRIP system – developed at the University of Salford then subsequently the University of Bristol - was initially designed to operate Linear Transfer Function models but, following the PhD research by Han (1991), was adapted to operate models of the PRTF type. The motivation for development of the PRTF approach (Physically Realisable Transfer Function) was to derive a form of Transfer Function model which would provide stable and non oscillatory output under all conditions. The PRTF formulation is now used for all new model development on the WRIP system.

- The IHACRES formulation (Jakeman *et al.*, 1990), which was developed by CEH Wallingford in collaboration with Centre for Resources and Environmental Studies (CRES) in Australia, is essentially a parallel pathway model with an effective rainfall pre-processor, and was initially developed for modelling rainfall runoff processes at a range of time scales (daily, monthly etc), and not specifically for flood forecasting.

- The DBM (Data Based Mechanistic) formulation (Young and Beven, 1994, Young, 2001) - developed at the University of Lancaster over the past 20 years – is a general framework for Transfer Function modelling, which holds that in the initial stages of model development the choice of model structure should remain as open as possible, with the optimum structure being identified from the information content in the available data. Two simple operational applications of this approach are to the Dumfries Flood Warning system in Scotland, which was implemented in 1991, and to the models currently used in Southern Region. Some modelling techniques which are options within the overall DBM approach are the use of observed flows for real time updating, and the Instrumental Variable method for model identification and calibration.

During the 1990s and to the present day, work has continued in developing all three of these approaches and some of these recent developments are discussed in the following sections. Regarding applications in the Agency and its predecessors, Figure 6.1 attempts to summarise the history and 'family tree' of the models which are currently used operationally or are under development.

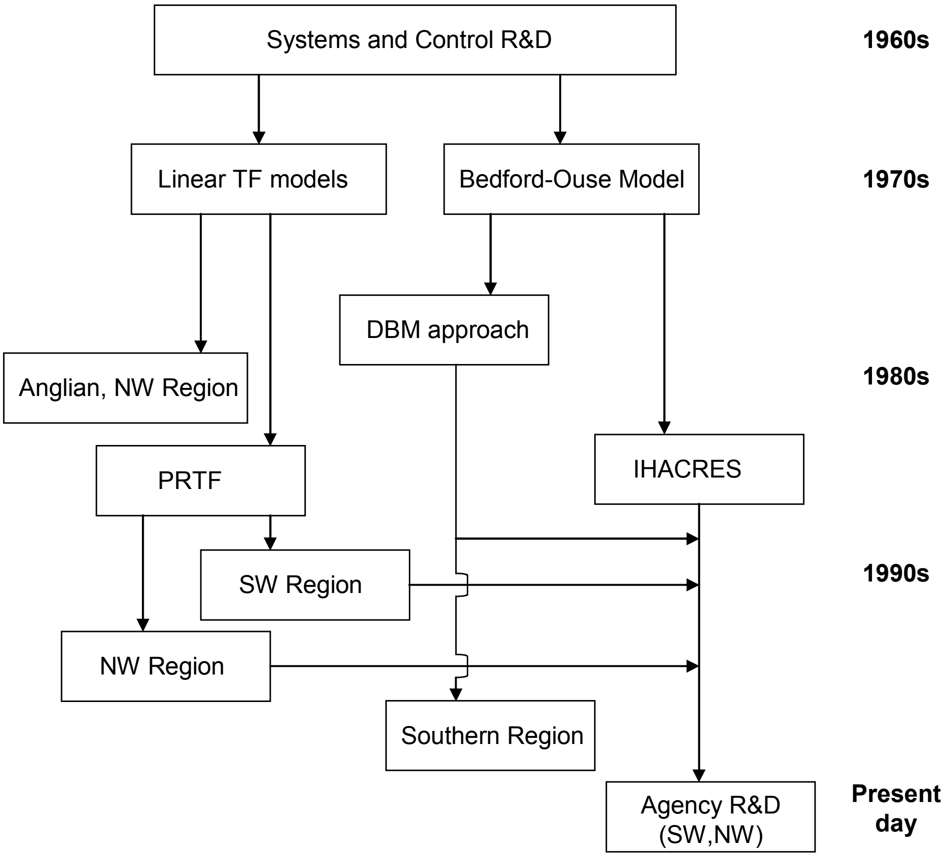

Figure 6.1 History of transfer function model development for current Agency applications

Terminology

A common problem encountered by hydrologists new to Transfer Function modelling is that the terminology used is unfamiliar and sounds at times highly statistical. However, this is in part because the historical root of Transfer Function models lies in the Systems and Control literature which - like hydrology - has its own specialised language and shorthand terminology for technical concepts. For flood forecasting applications, much of this terminology has been retained and this brief glossary provides defines some of the more commonly encountered terms in the research literature (e.g. Beven, 2000).

- Autocorrelation – the characteristic of a time series for successive values not to be independent i.e. to exhibit statistical correlation at one or more time steps apart
- Cross correlation – the characteristic of two or more time series not to be statistically independent i.e. to exhibit correlation between values
- Eigenvalues – in Transfer Function modelling, normally taken to mean the roots of the polynomial of a_i terms in Equation 2.1
- Equifinality – the tendency of some models to have many different parameter sets and model structures which describe the data equally well (also termed ‘non identifiability’)
- Hammerstein model – a Linear Transfer Function model with an effective rainfall pre-processor
- Heteroscedascity – usually describes the tendency for the variance of the residuals in the model results to vary with flow (if the variance is constant then the model is ‘homoscedastic’).
- Hybrid Metric Conceptual – if a metric model is purely data-based, and a conceptual model attempts to represent physical processes, then a hydrid metric conceptual (or ‘grey box’) model combines elements of both these types e.g. as in a non linear parallel pathway Transfer Function model
- Hypothetico Deductive approach – an approach to model development in which the structure of the model is decided in advance (a priori) based on the modeller’s views of the physical response of the catchment (see Inductive approach also)
- Inductive approach – an approach to model development in which the most appropriate structure for the model is inferred directly from the observed data, with any physical interpretation performed following this step (see hypothetico deductive approach also)
- Parsimony – the concept that a model should be no more complex than necessary to predict the observations to the required accuracy
- Recursive – the property of a model which means that it can be written in a form such that values at the current time step (e.g. flows) can be calculated from the values computed at previous time steps
- Residuals – usually taken to mean the remaining (‘residual’) error in a time series when comparing the observed and modelled output

6.2 Types of Model

The two main categories of Transfer Function model which are used for flood forecasting applications are:

- Linear Models
- Non Linear Models

and this section briefly describes some of the main formulations which have been proposed for operational use. The topics discussed include effective rainfall algorithms and approaches to model calibration and optimisation. Throughout, it is assumed that a discrete time formulation is used, rather than a continuous formulation, since the vast majority of models which have been reported in the literature for flood forecasting applications are of the discrete type (Young, 2001).

6.2.1 Linear Models

To discuss the various versions of these models which are used in flood forecasting applications, it is helpful to rewrite Equation 2.1 of Section A in the following form:

$$Q_t = \frac{b(B)}{a(B)} P_{t-T} \qquad (6.1)$$

where B is the backward shift operator defined by B_i y_t = y_{t-i} and a(B) and b(B) are now polynomial functions of the model parameters a_i and b_i. The ratio b/a is known as the model's impulse response function and the ratio ∑b/(1-∑a) is the steady state gain (which is sometimes considered as equivalent to a runoff coefficient).

As noted in Section A, a noise component η may also be included to model the time series of differences between observed and estimated flows:

$$Q_t = \frac{b(B)}{a(B)} P_{t-T} + \eta_t \qquad (6.2)$$

The model output (flows) is then said to consist of a noise free component and the noise variable. Although it is sometimes assumed that the noise component consists of uncorrelated, random variables, in practice individual terms may be correlated, and can often be represented by an Autoregressive Moving Average (ARMA) model of the form:

$$\eta_t = \frac{c(B)}{d(B)} \varepsilon_t \qquad (6.3)$$

where c and d are the parameters of the model and ε is an uncorrelated sequence of random variables with zero mean, and zero correlation with rainfall. This formulation is the classical Box-Jenkins or Transfer Function Noise model which is widely used in time series analysis (e.g. Box and Jenkins, 1970). Less restrictive assumptions can also be made; for instance retaining only the last of these assumptions. Calibration of the noise model also provides one possible route to real time updating, and is discussed in Section 6.3; however, for the remainder of this section, it will be assumed that no noise component is included.

For flood forecasting applications, one possible disadvantage of this form of the model is that the model output may be oscillatory, and is not constrained to produce positive flows. However, by careful selection of an appropriate model structure, and diagnostic tests on the model output (see later), it is generally possible to avoid these problems.

These considerations also led to the introduction of the PRTF formulation (Han, 1991) in which the roots of the polynomial a(B) are constrained to be equal, with the result that the a_i parameters are replaced by a single parameter, β say. Han also recast the equations in terms of the time to peak of the impulse function (tpeak), which loosely corresponds to the catchment time to peak, allowing β to be expressed in terms of tpeak alone. Analytical solutions for β can then be obtained for various assumed model structures, with a value of m=3 used for the PRTF models currently operated in South West and North West Regions.

One implication of the PRTF formulation is that the impulse response function is fixed by the value assumed for tpeak, so to allow for the possibility of varying catchment response, three additional parameters are introduced into the model controlling the shape, volume and timing of the peak via simple linear scaling relationships. This allows a simple form of model updating which is described in more detail in Section 6.3.

Of course, the linear formulations discussed so far do not allow for the influence of soil moisture conditions on runoff (i.e. the non linear relationship between rainfall and runoff), and the following two sections describe the two main approaches used to allow for this effect; estimation of effective rainfall, and a parallel pathway formulation.

6.2.2 Effective Rainfall Estimation

For Transfer Function models, many of the ideas for effective rainfall (or ‘rainfall excess’) estimation can be traced back to the early days of unit hydrograph modelling for flood estimation; for example the Flood Studies Report (predecessor to the Flood Estimation Handbook). The basic approach taken is to relate flows (perhaps less a baseflow component) to net or effective rainfall. For example, Reed (1984) presents four main categories of rainfall separation technique (see Figure 6.2):

- Constant Loss – losses are set to a value at the start of the event and remain at that value throughout the event
- Variable Loss – losses are assumed to reduce during the event as soil moisture increases (although independent of rainfall)
- Fixed Proportional Loss – losses are assumed to be a constant proportion of total rainfall at each timestep throughout the event, with the proportion depending on some measure of catchment state at the start of the event
- Variable Proportional Loss – losses are assumed to vary throughout the event depending on total rainfall at the current time step and some measure of the current catchment state

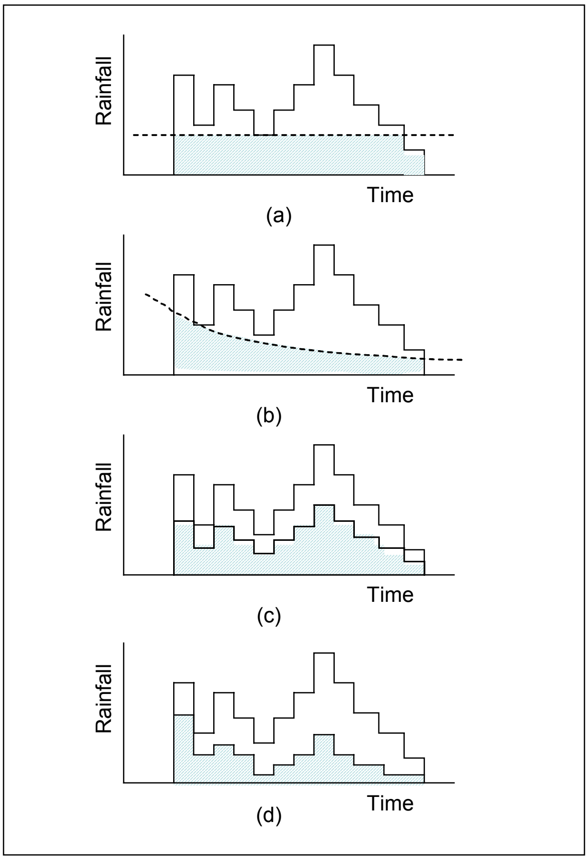

Figure 6.2 – Some examples of rainfall separation methods (adapted from Reed, 1984) (a) Constant Loss Rate (b) Variable Loss Rate (c) Constant Proportional Loss (d) Variable Proportional Loss

For Transfer Function models, the resulting time series of effective rainfall can then be used as input to the model.

To perform the rainfall separation, various parameters have been proposed as an indicator of catchment state, including the Catchment Wetness Index, Antecedent Precipitation Index, Soil Moisture Deficit, baseflow, current flow, and the time of year (either alone or in various combinations). Perhaps the key features of any approach should be that:

- The parameter(s) chosen are representative of catchment conditions
- The parameter(s) chosen are readily available (or can be computed) in real time, particularly if initialising the model after a gap in operations (e.g. due to telemetry failure, or starting up the model after a long dry spell)
- The parameter(s) chosen are available (or can be computed) at a time step comparable to that used in the model (e.g. hourly, 15 minutes)

Table 6.2 summarises some of the main candidates for inferring catchment state, and issues surrounding their use.

Table 6.2 Possible candidates for real time estimation of catchment state

Parameter	Typical timestep	Comments
Flow	15 minutes	Either the value at the start of the event, or values at the previous time step during the event. Used as an indicator of baseflow etc but mathematically leads to the apparent contradiction that effective rainfall depends on flow; however, entirely consistent with the 'black box' approach to modelling and widely used.
Air temperature	15 minutes if from an automatic weather station – usually daily or monthly	Used as a surrogate for evaporation; however, perhaps most suitable in arid/semi arid climates where evaporation is high relative to rainfall, and/or at longer timescales (e.g. monthly or seasonal) than those required for flood forecasting
Potential evaporation	15 minutes if from an automatic weather station – usually daily or monthly	Usually computed from air temperature, humidity, wind speed and net radiation – see comments above regarding air temperature
Catchment Wetness Index and other indicators of catchment state (SMD, API, model specific variables)	15 minutes if evaporation can be assumed constant	Typically computed from rainfall (15 minutes) and weekly MORECS values for evaporation. Leads to the apparent contradiction that a simple conceptual model is used within a 'black box' approach; however, entirely acceptable as a pragmatic approach to modelling flood flows.
MOSES	15 minutes on a 5km grid (or possibly 6 hourly for Agency applications)	New Met Office product – availability etc within the Agency to be determined and further R&D required. Performs continuous soil moisture accounting using a conceptual model and Nimrod and other inputs, shows strong potential for use in automated assessment of catchment conditions.

In the Transfer Function modelling literature, two well known approaches are the effective rainfall formulations which are used within the IHACRES and DBM approaches:

- IHACRES – Identification of Unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data - in this approach (Jakeman *et al.*, 1990), the effective rainfall component of the model estimates the current catchment state as a function of the state at the previous time step, rainfall in the current timestep, and an exponentially decaying function of air temperature. The model parameters consist of a scaling factor for air temperature (the ‘temperature modulation factor’), a time constant (‘mean residence time’) which determines the magnitude of the exponential term, and a constant which constrains the volume of effective rainfall to equal the total streamflow volume over the estimation period less the baseflow component at the start of the period (the ‘volume forcing coefficient’).

- DBM – the Data Based Mechanistic Approach (Young, 2001) optionally includes a non linear component which simply relates effective rainfall to a function of total rainfall and the flow at the previous time step. The reasoning behind this approach is that the flow is an indicator of catchment state. The only model parameters are a constant term, and the parameters in the function of flow (with a power law function typically used with an exponent in the range 0 to 1 – although other functions have been evaluated).

Both approaches estimate effective rainfall u as:

$$u_k = C\, r_k x_{k-T}^{\beta} \qquad (6.4)$$

where C is a constant, r is rainfall, k is the time step, x is the measure of antecedent conditions, and T a time delay. In the case of the IHACRES approach, x is the output from the soil moisture accounting model, T=0 and β=1 whilst, in the DBM approach, x is flow and C=1.

6.2.3 Multiple Pathway models

The parallel pathway approach provides another way of representing the complex interactions between rainfall and runoff (and is sometimes called the Threshold Approach). The basic concept is to separate the input rainfall, or effective rainfall, into two or more pathways with differing characteristics (residence times, time delays etc) and which, individually, are represented by linear models. Conceptually, for a 2 path model, this is often viewed as modelling the fast (surface runoff) and slow (baseflow) response of the catchment, although in the data-based approach it is important to note that separation into surface runoff and baseflow is only a conceptualisation or hypothesis regarding the reason for these differing timescales.

In an early review paper, Moore (1982) outlines two main approaches to formulating this type of model (Figure 6.3):

- Switching Threshold – in which the fast flow pathway ‘switches in’ above a certain value for catchment wetness
- Proportional Threshold – in which the split between the fast and slow response pathways varies throughout the event (e.g. with catchment wetness)

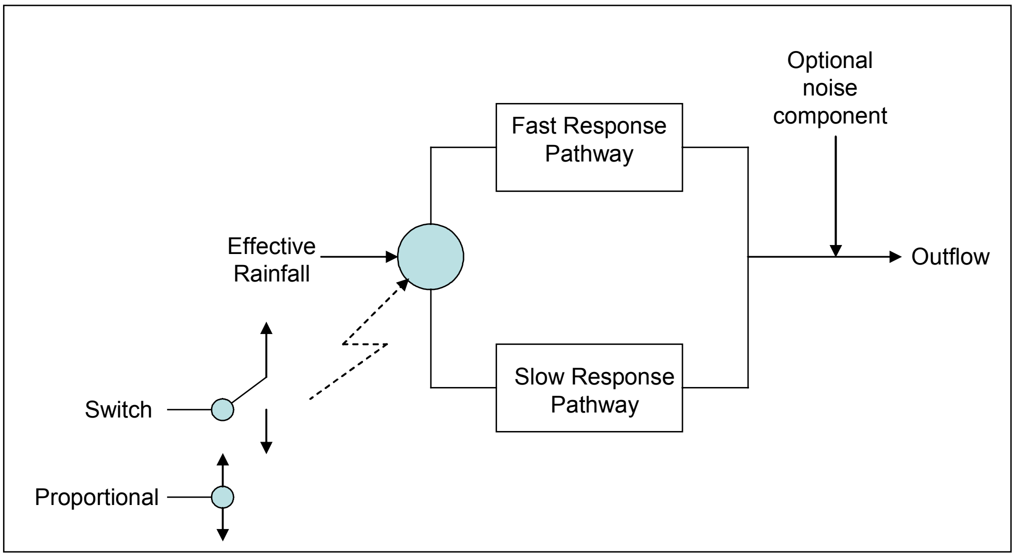

Figure 6.3 – Illustration of the switching threshold and proportional threshold approaches for a 2 path model

The idea behind the switching threshold approach is that the model can be optimised as usual for the flood flow response, but also represent the recession behaviour following an event (which can sometimes be difficult to achieve with a single pathway model). However, the proportional threshold approach is more widely used, and can be viewed conceptually as providing both slow (groundwater) and fast (surface runoff) pathways in proportions which depend on catchment state. An alternative view of the multiple pathway type of model is as a decomposition of a more complex linear model since, in general, any Linear Transfer Function model with an order greater than 1, and real eigenvalues (i.e. real roots of the polynomial a(B)) can be decomposed by partial fractions into a series or parallel pathway form, depending on the form of the numerator term (Young, 1992). The number of 'paths' or sub-models can be greater than 2, for example to include fast response, slow response, and instantaneous response units in various permutations.

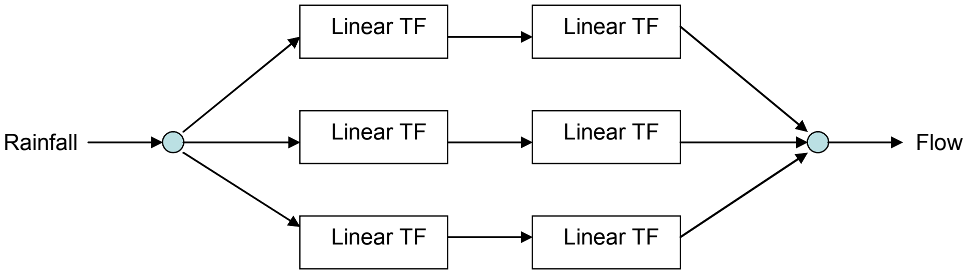

Figure 6.4 – Multiple pathway model with series and parallel components (adapted from Lees, 2000)

However, the most studies to date have suggested that a maximum of 3 distinct response units is sufficient for modelling flood response, with 2 usually being sufficient. For example, in an analysis of seven catchments world-wide, Jakeman and Hornberger (1993) found that the parallel pathway formulation with 2 paths was the optimum approach in all cases.

The issue of whether to specify the model structure in advance (a priori), or to infer the model structure from the data, is a matter which has received much attention in the literature. For example, many of the models which are presently used operationally are of a defined type (e.g.

the PRTF and IHACRES models). However, there is also a widespread view, exemplified in the Data Based Mechanistic approach (e.g. Young and Beven, 1994), that as few prior assumptions should be made as possible, and that the optimum form of model should be inferred from the data. This issue is discussed further in the following section.

6.2.4 Modelling Procedure

The main stages in the modelling procedure are usually:

- Model identification – to identify the appropriate structure for the model
- Model calibration – to calibrate the parameters of the model (also called optimisation or estimation)
- Model validation – to validate the model against datasets not used in the original calibration (e.g. using some of the performance monitoring measures discussed in Chapter 4.4)

The generic modelling specification under development by the Agency (see Section 2.4) is modularising these steps and the following sections discuss these individual steps in general terms (although the detail may change within the overall framework):

Model identification

The aim of this step is to identify an appropriate structure for the model, where the structure can include whether a multiple pathway model is to be used, and the form of any effective rainfall estimator. Beven (2000) notes that, for any given modelling problem, there may be no unique answer to this problem, for reasons which may include:

- The (usually) complex non linear relationships between rainfall and flow
- Errors in the input data (rainfall, flows)
- Discretisation errors (e.g. the optimum time delay may not be a whole number of time steps)

Instead, the objective is to find a model structure which provides a good fit but is parsimonious in the sense of having as small a number of parameters as possible which are statistically significant whilst providing an acceptable model ‘fit’ to the data.

Perhaps the first consideration is the optimum time step to use in the model. For example, Jakeman and Hornberger (1993) note that too coarse a sampling interval will result in a loss of information about response dynamics, whilst too fine an interval can result in numerical instabilities. Also, a timestep which is too short may make the model output more sensitive to disturbances (errors etc) in the input data. The appropriate sampling interval to select is therefore the one that is of the order of, but preferably less than, the time constant of the quickest identifiable response (although this selection can make identification of slower components numerically difficult).

In Agency practice, the standard sampling interval for telemetered data is 15 minutes, which constrains model outputs to this interval, or multiples of 15 minutes. However, at the start of the model identification process, the response timescales are not yet known, so it may be necessary to try different assumed timesteps as part of the initial assessment of the best form of model to use. Also, the use of continuous-time formulations for Transfer Function models is an active area of research (e.g. Young, 2004), and offers the potential to avoid adoption of a fixed modelling time step (although if discrete interval input data are used some assumptions need to be made about the response over each interval e.g. via an additional sub-model).

Similarly, some iteration may be required to find the best compromise regarding the error of fit. In Section A, some measures of goodness of fit which were discussed included the efficiency R^2 (also called the Coefficient of Determination, the Nash Sutcliffe efficiency, and the R^2 statistic), the peak flow error, and more sophisticated measures arising out of time series analysis theory, such as the Akaike Information Criterion, which are designed to assist in identifying the model order (Akaike, 1974). It was also noted that the criterion (or criteria) chosen should reflect the purpose of the model, and might consider the whole hydrograph, the rising limb, or values above a threshold (e.g. the Severe Flood Warning level).

Identification of the optimum number of parameters

Often, as the order of the model is increased, the goodness of fit may improve, but the standard error (or uncertainty) in the parameters may increase. Some consequences of an overparameterised model may include oscillatory or negative outputs, and oversensitivity to rainfall inputs, particularly outside the calibration range. To provide some measure of this trade-off between improved fit, and increasing standard errors, Young (e.g. Young, 1992) introduced the Young Information Criterion (YIC), which is the sum of two terms which are functions of the ratio between the variances of the model residuals and of the modelled flows, and of the mean normalised error variance in the model parameters. The functions are logarithmic and, in both cases, become more negative as the model fit / parameter estimates improve, so that minimum values of the YIC measure are therefore useful in the model identification stage as a guide to the acceptability of a proposed model structure. Jakeman *et al.*, 1990 use a similar, but slightly simpler measure, which is the average parameter error (as a fraction) across all parameters together with the R^2 statistic.

Model identification can be performed either with a certain structure of model in mind (e.g. a simple linear model based on total rainfall), or by trying various configurations of model, and allowing the data to indicate the most appropriate form. Young (2001) describes these two approaches as the hypothetico-deductive approach, based on the preconceptions regarding hydrological response by the modeller, and the inductive approach, in which the form of model is inferred from the data.

The two main types of Transfer Function model currently used within the Agency are linear models operating from total rainfall (and the PRTF variant), and the DBM type of model. In the case of the PRTF formulation, the number of flow parameters (m) is usually fixed at 3, but the number of rainfall parameters (b), and the value for the time delay (T), can be varied by ‘trial and error’ to see the impact on model fit parameters such as the Akaike Information Criterion and the R^2 statistic.

By contrast, in the Data Based Mechanistic (DBM) approach (e.g. Young, Jakeman, McMurtrie, 1980; Young, 2001), the choice of model structure is left as open as possible in the initial stages of model development. The model may use total or effective rainfall, have single or multiple pathways, have parameters which are constant or vary in time, and so on. The procedure used is to assume a range of possible structures and, for each structure, to compute measures of fit such as the efficiency R^2 and the Young Information Criterion. Typically, it will be found that the estimates for parameter errors will increase sharply beyond a certain number of parameters, but that the R^2 values will tend to level out above a certain threshold, and that often there will be a number of models with comparable performance in this ‘plateau’ area. In this case, the most parsimonious (or minimal, dominant mode) model structure can be selected as a reasonable compromise. A parallel pathway interpretation may also be made, depending on the number of rainfall and flow parameters identified and the eigenvalues of the flow polynomial (see Section 6.2.3).

One additional complication occurs if an effective rainfall formulation is to be used, requiring an iterative approach to model identification. For example, Jakeman *et al.* (1990) propose a staged approach to model identification which, in slightly adapted form, is:

1. Use prior information to specify the ranges to be explored for the model order (m,n,T) and effective rainfall model
2. For each candidate model order, compute the parameter errors and R^2
3. Select an initial model order by trading off the two statistics in Step 2.
4. For the model order selected in Step 3, calculate the parameter errors and any other model fit statistics deemed important for each candidate parameter set in the effective rainfall model
5. Repeat Step 2 to check that the candidate model order remains the same
6. Perform diagnostic and validation checks on the preliminary model(s)

It is noted that, if the relationship between rainfall and flow is highly non linear, then Step 5 is likely to show that some revision of the model order is required. Also, for the IHACRES formulation, it has been found that the optimum model order is reasonably insensitive to the value for the time constant parameter assumed in the effective rainfall formulation, which greatly cuts down the number of model orders to be evaluated.

Some indication of model structure can also be obtained using classical time series analysis techniques. For example, Reed (1984) and Whitehead (1975) note that an appropriate structure can sometimes be deduced from an estimate for the impulse response, calculated as the cross correlation of the transformed ('pre-whitened') rainfall and flow series. Here an ARMA or similar model is used to transform the data into a series of approximately uncorrelated values. An indication of the most appropriate values for m, n and T can then be obtained by examining the shape and timescale of this calculated function.

Model Calibration

Once the model structure has been identified, the aim of the calibration process is to find the optimum parameter values for that structure. Often, parameters are estimated using one of the following two techniques:

- Recursive Least Squares
- Instrumental Variable

Recursive Least Squares

One of the most widely used approaches is the Recursive Least Squares (RLS) method (e.g. Young, 1974; Han, 1991). Here, the objective is to minimise the sum of the squares of the differences between observed and estimated flows (often called a 'cost function'). This requires that all of the partial derivatives with respect to the model parameters should be set to zero, resulting in a set of linear simultaneous algebraic equations which can be optimised to the estimated model parameters.

The term ‘recursive’ arises from rewriting the estimation equations in a form which can be applied at each time step, based on the estimate from the previous time step. By incorporating assumptions about the statistical characteristics of the model noise, it is also possible to derive estimates for the accuracy of the model parameters at each time step. Recursive formulations require starting values for the estimation process, and possibilities include assuming values based on observed data (e.g. at the start of the event), or adopting ‘a priori’ values which reflect the level of confidence in the initial estimates (which will often be low).

One approach to model structure identification

The Data Based Mechanistic (DBM) approach offers one method for identifying the most appropriate model structure and is as follows (adapted from Young, 2001).

1. Setting Objectives The important first step is to define the objectives of the modelling exercise and to consider the type of model that is most appropriate to meeting these objectives. The prior assumptions about the form and structure of this model are kept at a minimum in order to avoid the prejudicial imposition of untested perceptions about the nature and complexity of the model needed to meet the defined objectives.
2. Objective Identification of Structures An appropriate model structure is identified by a process of objective statistical inference applied directly to the time-series data and based on a given general class of linear transfer function models whose parameters are allowed to vary over time, if this seems necessary to satisfactorily explain the data.
3. Refining Step 2 for Linear Models If the model is identified as predominantly linear or piece-wise linear, then the constant parameters that characterise the identified model structure in Step 2. are estimated using advanced methods of statistical estimation for dynamic systems. For example, the Refined Instrumental Variable (RIV) and Simplified RIV (SRIV) algorithms provide a robust approach to model identification and estimation that has been well tested in practical applications over many years.
4. Refining Step 2 for Non Linear Models If significant parameter variation is detected then the model parameters are estimated by the application of an approach to time (or state) dependent parameter estimation based on recursive Fixed Interval Smoothing (FIS). Such parameter variation will tend to reflect nonstationary and nonlinear aspects of the observed system behaviour. In effect, the FIS algorithm provides a method of non-parametric estimation, with the Time Variable Parameter (TVP) estimates defining the non-parametric relationship, which then can often be interpreted in State-Dependent Parameter (SDP) terms
5. Identifying Effective Rainfall If nonlinear phenomena have been detected and identified in stage 4, the non-parametric state dependent relationships are normally parameterised in a finite form and the resulting nonlinear model is estimated using some form of numerical optimisation, such as nonlinear least squares or Maximum Likelihood based on prediction error decomposition. This approach to nonlinear identification and estimation is required only to define the nature of the effective rainfall nonlinearity, which appears only at the input to the model
6. Final Testing Finally, the estimated model is tested in various ways to ensure that it is conditionally valid, and both describes the data well and provides a description that has direct relevance to the physical reality of the system under study. This involves standard statistical diagnostic tests for stochastic, dynamic models, including analysis which ensures that the nonlinear effects have been modelled adequately as well as exercises in predictive validation and stochastic sensitivity analysis.

Recursive methods can also be extended to allow for the possibility of changes in parameter values over time; for example by assuming a simple random walk model if it is thought that the parameters are slowly varying in time. In this form, there is a strong similarity with the well-known Kalman filter estimation approach for stochastic systems. In Kalman filtering, the 'state' of a linear system is estimated from a number of 'noisy' observed values – where in the case of a flow forecasting application the 'state' would be the flows, and the observed values the rainfall, contaminated by observation and other errors.

As an example of application of this approach, Figure 6.5 illustrates the Recursive Least Squares based calibration procedure for an early version of the PRTF model (Han, 1991):

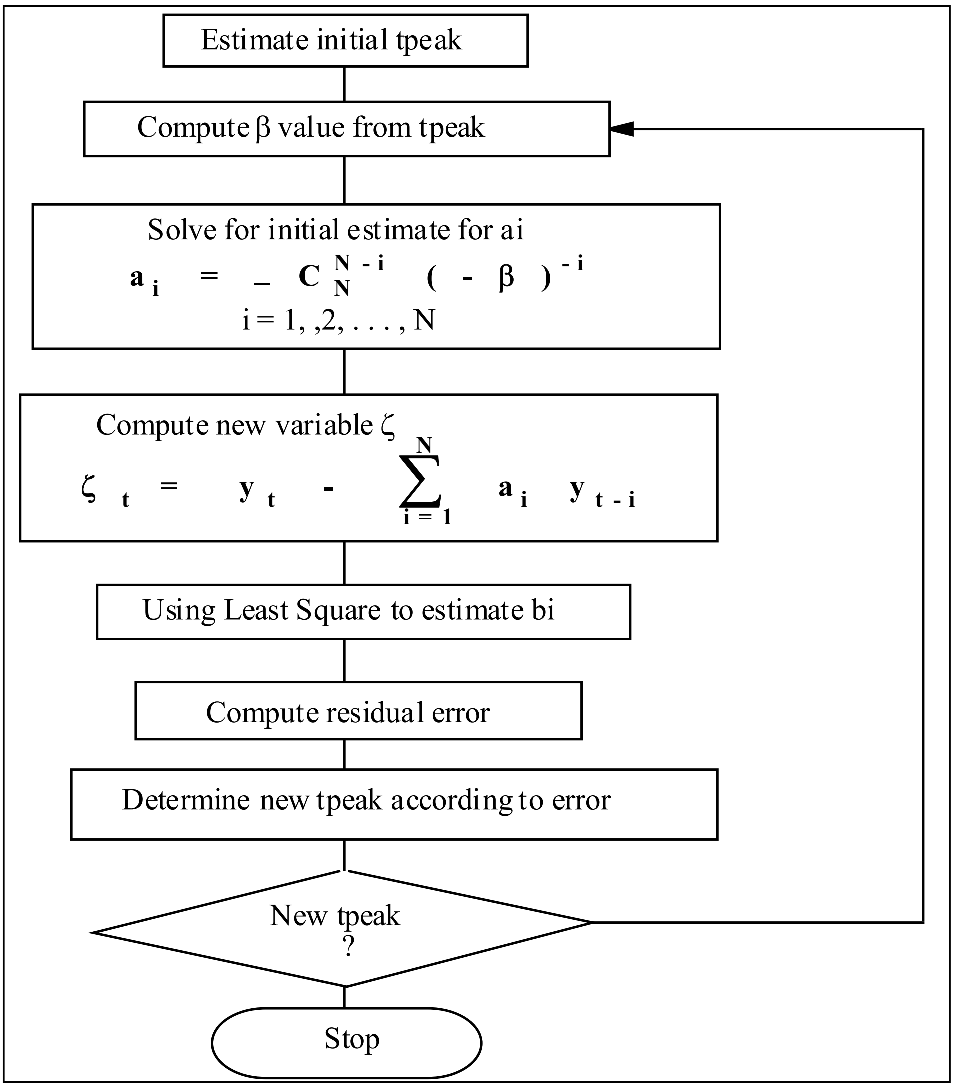

Figure 6.5 – Flowchart for PRTF model calibration (Han, 1991)

Here, the terms a_i, tpeak and β are defined in Section 6.2.1 and it should be noted that, in the step 'Solve for initial estimate for a_i' this of course only applies on the first iteration (with the updated values being used on subsequent iterations).

Instrumental Variable approach

An alternative approach – the Instrumental Variable (IV) approach and variants (e.g. the Simplified Refined Instrumental Variable – SRIV approach; Young 1992) – has some similarities with the Recursive Least Squares approach, but can allow for less restrictive assumptions about the statistical characteristics of the noise term (Young and Wallis, 1985). The term 'Instrumental Variable' refers to an auxiliary variable (in fact a vector) introduced into the analysis which is chosen to have maximum correlation with the noise free component of the model output, but to be totally uncorrelated with the noise term (i.e. it is an estimate for the noise free system output). For the noise term, in the basic recursive Instrumental Variable (BIV) approach, the only assumption is that the noise is statistically independent of the input variables (rainfall).

So-called optimal, or refined, versions of the Instrumental Variable algorithm are also available for the case that more restrictive assumptions are made regarding the noise term i.e. that a model is assumed for the statistical characteristics of the noise term. For example, a Refined Instrumental Variable algorithm can be derived for the Box-Jenkins model described in the previous section, where an autoregressive (ARMA) process is assumed and the analysis is performed in terms of transformed (prefiltered) versions of the data. RIV estimates might be expected to have lower estimation error variance, although at the expense of some assumptions – perhaps incorrect – about the nature of the noise term.

Comparison of Methods

Of these various estimation schemes, the choice of method will depend on the computational efficiency of the scheme, and its statistical performance. Jakeman *et al*. (1990) considered the following characteristics of four different calibration approaches in relation to the IHACRES model and listed some of the following benefits of each approach:

Table 6.3 – Properties of four estimation techniques (adapted from Jakeman *et al*., 1990)

Property	RLS	BIV	SRIV	RIV
Unbiased	No	Yes	Yes	Yes
Consistent	No	Yes	Yes	Yes
Stable to outliers in data	Yes	No	Yes	Yes
Asymptotically efficient	No	See below	See below	Yes
Slow response identification	Poor	Poor	Strong	Strong

The computational complexity, in terms of number of steps for convergence, was also identified as increasing from the RLS approach (simplest), to the BIV and SRIV (similar), with the RIV approach highest (although with modern computing processors this is probably no longer an issue). For the BIV and SRIV approaches, the asymptotic efficiency is good only if the model residuals are not autocorrelated, have zero mean and constant variance.

From the table, the implication is perhaps that the SRIV and RIV approaches offer the most advantages, particularly for parallel pathway models (i.e. with a slow response pathway), although usually at the expense of some additional computational requirements. This is particularly the case during the model identification stage, if the model structure is to be inferred directly from the data. The resulting models may also be more parsimonious than those indicated by less efficient algorithms.

However, this should not rule out use of the popular RLS and BIV approaches, which are widely used and offer a pragmatic alternative to model fitting. For example, for the RLS approach, estimates may be close to being unbiased, consistent and asymptotically efficient where autocorrelations are small, have zero mean, and only a small cross correlation with the rainfall (and checks on the autocorrelation, variations with time and flow, and distribution of the residuals should ideally be made once the model is fitted).

This is particularly true when the automated calibration is only used as a starting point for estimation of the model parameters, or if other criteria than the least squares fit are important e.g. the ability to match the magnitude and timing of peaks. Also, in practice, greater improvements in model accuracy may come from putting effort into the selection (and calibration) of appropriate catchment rainfall averaging, effective rainfall and updating routines, rather than from the precise choice of optimisation procedure which is used.

It should also be noted that other forms of model calibration procedure have been proposed in the research literature; for example stochastic Bayesian approaches which make initial ‘a priori’ assumptions about the nature of the model, and Maximum Likelihood estimators, which are confined to certain pre-defined forms of model.

Having identified a model structure, and calibrated the parameters, an important final step is to examine the characteristics of the resulting model both for performance, and physical response. These checks include calculating the steady state gain (interpreted as a pseudo runoff coefficient) and the impulse response (shape and response time), and validating the model on datasets not used in the original calibration. Also, the statistical characteristics of the noise component of the model should be examined to check that they are consistent with the assumptions made in the model calibration algorithm including that they are uncorrelated with the input rainfall.

6.3 Real Time Updating

Real time updating is perhaps the key feature which distinguishes real time flood forecasting models from off-line simulation models, and provides the potential for major gains in model accuracy. In Section A, three main categories of updating were identified as follows:

- Error Prediction
- State Updating
- Parameter Updating

and examples of updating approaches were provided within each of these categories. The aim of this section is to provide more background on these various approaches and to describe some of the advantages and disadvantages of each method.

6.3.1 Error Prediction

Analyses of model output during flood events often suggest that the differences between the model results and observed flows tend to show some consistency, with the model overpredicting or underpredicting for long periods of time during the event, or showing a consistent time delay between observed and forecast peak flows.

The aim of error prediction is to model these error sequences up to the time of the latest observation, and then to extrapolate these trends into the future. The forecast error sequences can then be applied to the uncorrected forecasts to derive updated estimates for the forecast flows.

Error prediction methods have the characteristic that they are independent from the underlying model, and so have no influence on the model output or calibration, with less risk of model crashing due to model instabilities etc. It is also computationally straightforwards to present displays of the model output with and without updating.

For conceptual models, error prediction is perhaps the most widely used approach within the Agency, although it does not appear to have been applied operationally for Transfer Function models.

Graphical Correction

In the graphical correction approach, the trend in model errors is identified either ‘by eye’ or automatically, and then a decision is taken by the forecaster on whether (and how) to extrapolate that trend into the future. Options include shifting the hydrograph along the time axis (for timing errors), assuming an average error up to ‘time now’ which will persist into the future, or blending the observed and forecast flows by distributing the error over the forecast lead time, such that the forecast matches the observed values at time now, and has zero correction applied at the maximum lead time. Although simple, graphical techniques can be successful particularly for correcting timing errors (since many of the more sophisticated techniques do not handle these well). For example, the human eye can often instantly spot trends or timing errors which might not be detected by a computer algorithm. The graphical approach is widely used overseas and is currently used in a qualitative way within the Agency for Transfer Function models i.e. a forecaster takes a view on whether the model is over or underpredicting based on comparison of the observed and forecast flows.

Time Series models

When used for updating, a time series model aims to model the time series of residuals, and typically incorporates autocorrelation and random elements (e.g. an Auto Regressive Moving Average - ARMA - model). For Transfer Function modelling, this approach has many similarities to the Transfer Function Noise approach (see later), except that the noise model is fitted separately from the main Transfer Function model, and plays no part in the model identification or optimisation phases.

Models of this type exploit the persistence in errors which is often observed in model outputs; for example, consistent over or under prediction. However, known difficulties with this approach (e.g. Moore, 1982) are that timing errors can lead to rapid changes in the sign and magnitude of errors, particularly around the peak flow (which is one of the main parameters of interest). Updating is therefore 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. Also, implausible behaviour may occur if errors are random in time rather than following the underlying assumption of persistence in flows. A typical characteristic of error prediction routines is that the correction decays towards zero at the maximum lead time of the forecast.

Pattern Matching

The pattern matching approach aims to improve on the graphical approach by using repeated sampling in real time to identify adjustments to the input rainfall data (timing and magnitude) so that the output better matches observed flows. 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 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 adjustments to be applied to the input data to take the errors into account during the forecast period.

6.3.2 State Updating

State updating techniques aim to adjust the 'state' of the model in real time to compensate for any differences observed between observed and forecast flows. The term 'state' is perhaps most easy to understand for physically based models, where it might apply to the water content of a store in conceptual model, or a reservoir level in a hydrodynamic model, for example. In Transfer Function modelling, the state is usually interpreted as either the model output (flow) or catchment state (if an effective rainfall approach is used).

The following sections describe the main types of state updating routine applied to Transfer Function models, and of these both the flow substitution and adaptive gain approaches have been used operationally within the Agency.

Flow Substitution

The flow substitution approach is perhaps the simplest approach to updating available (e.g. Reed, 1984), and simply consists of replacing the forecast flows at each time step up to and including 'time now' with any observed (telemetered) values which are available. The forecast is then automatically constrained to match the observed flow at 'time now' (assuming that a telemetered value is available), and is strongly influenced by the observed values for short lead times.

Adaptive (or Time Varying) Gain

The adaptive gain approach[2] simply applies a single scaling factor to the input rainfall data (or rainfall parameters) to compensate for any differences between observed and forecast flows. The single gain parameter can be estimated recursively i.e. from the value at the previous time step and a function of the current prediction error, using the TVP methods described in Section 6.3.3. Typically, the value for the gain is found to vary slowly around a value of 1, depending on whether the model output is over predicting or underpredicting flows. To avoid sudden changes in response, the changes in gain can be filtered (smoothed) via an additional parameter which provides a linear weighting between the gain at the current and previous time steps (Cluckie and Owens, 1987) or via a Noise Variance Ratio parameter (Beven, 2000). This approach to updating has been used in both Anglian and South West Regions (see Appendix A), and in a forecasting system for the town of Dumfries in Scotland (see Fact Sheet C).

Kalman Filter

This form of updating (e.g. Cluckie et al., 1982, Lees, 2000, Young and Tomlin, 2000) aims to estimate the optimal state (i.e. flow) in real time by application of the Kalman Filter approach (for linear models) and the Extended Kalman Filter (for non linear models). Kalman Filtering is a widely used technique in control theory to infer best estimates for the state of a system from both observations and models contaminated by noise. For example, for an industrial process, the state

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[2] Note that Adaptive Gain updating can be viewed as either a form of state updating (compensating for uncertainties in catchment rainfall estimates), or parameter updating (compensating for uncertainties in the model parameters)

of a chemical reaction might be determined from data provided by several hundred sensors recording (inaccurately) different aspects of the process. In the case of rainfall runoff modelling, the 'state' to be inferred is the flow output uncontaminated by measurement noise. For example, Young and Tomlin 2000 present an example of this approach for a parallel pathway model for the river Hodder in North West England, where the state variables are the unknown flows in the two pathways each contaminated by white noise stochastic terms. The solution equations can be expressed in predictor-corrector form and solved recursively for each time step up to the maximum lead time of the forecast. Kalman Filtering approaches can also be used for parameter updating (e.g. Young and Wallis, 1985).

6.3.3 Parameter Updating

In parameter updating, the inherent assumption is that – given the limited datasets available for model calibration, and intrinsic measurement errors etc – it is not possible to derive a single model with fixed parameters valid for all situations. Instead, the model parameters are updated during an event to account for uncertainties in the model calibration and data. For a Transfer Function model, the parameters can include the flow and rainfall parameters (a_i, b_i), the noise model parameters (if applicable), and any parameters used in the effective rainfall estimator (if applicable).

PRTF approach

This approach is specific to the PRTF formulation of model (Han, 1991) and aims to apply a combination of timing, scaling and shape corrections to the forecast hydrograph whilst retaining the constraint of non oscillatory and positive model outputs.

In the PRTF formulation, three additional parameters are introduced into the model to control the volume, shape and timing of the hydrograph. These parameters are chosen so as to retain model stability, and have the effect of adjusting the scale, timebase, and timing of the impulse response function as follows:

- The volume parameter applies a linear adjustment to the rainfall parameters b_i
- The shape parameter adjusts the tpeak value which is assumed
- The timing parameter adjusts the time delay T which is assumed

Within the Agency, PRTF models are solely operated within the WRIP system environment, and the user interface includes three 'slider' controls (like volume controls on a TV) which allow these parameters to be adjusted manually so that the hydrograph more closely resembles the observed values (either in appearance, or in terms of error of fit statistics). However, operators report that:

- Some guidance is required on the appropriate adjustments to make in real time
- In a widespread event, there is not time to make manual adjustments at all sites every 15 minutes (as would occur with an automated approach, for example)
- In some cases, it is not clear whether the main aspect of the forecast to adjust is a timing error, or magnitude error, or some combination of the two

South West Region has therefore recently taken the lead in exploring ways of automating this approach (see Appendix A1.3), and for all new model development look up tables are generated giving indicative values for these adjustment factors depending on catchment state (in this case Catchment Wetness Index, which is one of the outputs automatically computed by WRIP).

Transfer Function Noise

The Transfer Function Noise formulation includes a noise component to account for the remaining uncertainties in model output, and has many similarities to the time series error prediction approach, except that the noise model is jointly calibrated with the simulation parameters. Although other assumptions can be made, typically an ARMA(p,q) model is used in which the autocorrelation and/or random parameters in the noise model component are varied during an event. The ARMA model is usually initialised by assuming that, at the start of the event, the noise term is zero and can be used to derive forecasts at one or more time steps ahead. A typical characteristic of this updating approach is that the updated forecast (i.e. incorporating the noise component) will tend towards the simulated value at long lead times. To fit the ARMA model, typically the mean square error is minimised, and this operation can be performed for as many forecast lead time as required, leading to multiple models optimised for each lead time. Moore (1982) notes that three different formulations can be derived for the noise predictor based on information available at time now; the so-called Innovation, Output and N-step ahead predictors, with the Output form more parsimonious for models of autoregressive form (i.e. ARMA(p,0)). For UK catchments, a model order of 3 or 4 (ARMA(3,0) or ARMA(4,0)) often provides an acceptable forecast correction (Environment Agency, 2000).

Time Variable Parameter (TVP)

The Time Variable Parameter (TVP) approach to updating operates on parameters of a model in order to compensate for the non linear response of flow to rainfall during an event. Typically, for a rainfall runoff model, model identification procedures often suggest the flow parameters can be assumed constant, whilst the rainfall (input) parameters vary over time due to non linear influences, so this type of updating is normally performed only on the rainfall parameters of the model.

The parameter values are revised at each time step using recursive forms of estimation techniques such as the IV algorithm or Kalman filtering (e.g. Young, 1974; Whitehead, 1975, Lees, 2000, Beven, 2000). Various forms of parameter variation may be assumed; for example a simple random walk process in which the parameters are constrained to vary slowly in time, or a smoothed or integrated random walk. This approach was evaluated in the Dumfries forecasting model described in Factsheet C, and provides an alternative to using an effective rainfall estimator, since the non linear response is accommodated through allowing the rainfall parameters to change.

Genetic Algorithm

Genetic Algorithms – a type of evolutionary computing – use a structured form of random sampling to determine the optimum parameters of a model (e.g. Wang, 1991, Beven, 2000). Parameter sets are selected at random and then allowed to evolve over successive generations, following a variety of possible rules for ‘evolution’. This can be an efficient and robust method for solving difficult optimisation problems where simpler methods fail, or where there may be more multiple peaks, discontinuities, ridges or plateaus on the response surface (e.g. two or more parameter sets providing similar ‘fits’ to the data). In the so-called shuffled complex evolution approach, genetic algorithms are combined at each successive step with classical ‘hill climbing’ parameter search techniques, allowing a rapid search to be performed for the optimum parameter set over the response surface. For Transfer Function forecasting applications, the aim is to provide an optimum fit to observed and forecast flows for times up to ‘time now’. Genetic Algorithms, and shuffled complex evolution methods, are being evaluated by South West Region as one possible approach to real time updating of PRTF models.

7 MODEL ACCURACY AND UNCERTAINTY

A common question asked by practitioners is what accuracy can be expected from a Transfer Function rainfall runoff model? However, this issue is complex, and depends on a number of factors including:

- The accuracy and representativeness of the input data (e.g. raingauge or radar rainfall)
- The accuracy of the flow data used for calibration and – possibly – updating (particularly at high flows)
- Catchment specific issues (reservoirs, floodplains, groundwater influences, role of antecedent conditions etc)
- The model structure (order, number of pathways, effective rainfall formulation etc)
- The statistical efficiency of the model identification and optimisation routines
- Whether real time updating is used (and the type of algorithm employed)
- The criteria being used to assess the model's performance (peak levels, timing, rising limb, full hydrograph measures etc)
- The model time step used

It is therefore not possible to give a simple assessment such as "the accuracy in peak levels should usually be within 0.25m" or "an R^2 value of 0.8 or more is acceptable". Instead, the key factor to consider is whether the model provides output which is acceptable for the intended application for a range of test cases in addition to those used for the initial calibration (the principle of 'horses for courses').

This chapter explores some of these issues and, whilst no definitive answers are provided, should give some indication of the typical performance of Transfer Function models in various situations, and ways of assessing uncertainty. Section 7.1 begins with a discussion of model accuracy, then Section 7.2 discusses sources and estimation techniques for uncertainty.

7.1 Model Accuracy

As part of this project, a brief review has been performed of model accuracies reported in the literature, and Table 7.1 summarises some of the main sources of errors in model output.

The performance of Transfer Function rainfall runoff models is traditionally assessed in terms of the R^2 statistic, and sometimes in terms of peak levels or flows. However, as noted in Chapter 4, a range of other measures might be appropriate in flood forecasting applications, including threshold crossing measures, and values at given forecast lead times, although model accuracies are rarely quoted in these terms.

For example, Jakeman and Hornberger (1993) note that the parallel pathway IHACRES formulation appears to fit a wide range of catchments reasonably well, with R^2 values typically greater than 0.80, based on tests on around 50 catchments (although possibly only for daily data).

For flood forecasting applications, other studies have shown a wider range of variations in R^2, as illustrated in Table 7.2(a) for the case of models with no updating routines in place (i.e. simulation mode only).

Table 7.1 Some principal sources of uncertainty in transfer function 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
	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, representation of antecedent conditions)
	Model resolution	Time step is insufficient to resolve the spatial and temporal scales of the event (floodwave, storm etc), or too small resulting in too many model parameters
	Poor model performance in real time	Oscillations or physically unlikely flows
	Operator errors	Problems or misconceptions in calibrating or running the model

Table 7.2(a) Model performance for selected catchments (simulation mode)

Reference	Catchment	Area (km^2)	Catchment Type	Model Type	R^2	Peak flow error (%)
Moore (1982)	Frome (South West)	206	Lowland, chalk	Linear	0.24	
				Effective Rainfall (CWI)	0.3-0.4	
				Parallel Pathway (switching threshold)	0.25-0.46	42
	Eden (North West)	69	Upland, impervious	Linear	0.76	
				Effective Rainfall (CWI)	0.73-0.76	
				Parallel Pathway (switching threshold)	0.78-0.82	28
	South West Wales	0.72	Small, upland	IHACRES	0.95	
	Afon Camddwr, South West Wales	0.34	Small, upland	IHACRES	0.85	
Young (1992)	South West Wales		Small upland	DBM	0.94	
Lees (2000)	Bolyneendorish (Ireland)		Fast response	Linear	0.76	33
				DBM	0.80	17
Young and Tomlin (2000)	Hodder (North West)			DBM	0.87	

Although it is difficult to draw general conclusions from these results (since they use different models, on different catchments), it can be seen that – at least for the studies listed:

- Model performance is considerably better for small fast response catchments than large lowland catchments
- Model performance generally increases with increasing model complexity (e.g. parallel pathway, effective rainfall estimation)
- R^2 values of 0.8 or more are achievable for small fast response catchments

Table 7.2(b) shows a similar set of results for models including real time updating, from which it can be seen that updating produces dramatic improvements in model fit, with R^2 values of 0.95 or more in these examples.

Table 7.2(b) – Model performance for selected catchments – updating mode

Ref.	Cmt	Area (km^2)	Catchment Type	Model Type	Lead Time (hrs)	R^2	Peak Flow error (%)
Moore (1982)	Frome (South West)	206	Lowland, chalk	TFN - Effective rainfall (variable loss)	1		22
					3		39
					6		-
	Eden (North West)	69	Upland, impervious	TFN - Parallel Pathway (switching threshold)	1		7
					3		38
					6		1
Lees (2000)	Boyneendorish (Ireland)		Fast response	Error Prediction	1	0.98	
				Kalman Filter	1	0.98	
				Flow Substitution	1	0.98	
				Adaptive Gain	1	0.94	
Young and Tomlin (2000)	Hodder (North West)			DBM with noise component	1	0.96	

7.2 Assessment of Uncertainty

7.2.1 Introduction

No model provides a perfect representation of reality and all types include some residual uncertainty in the modelled output. However, perhaps one of the main distinguishing features of Transfer Function models is that they are stochastic in nature, allowing a formal assessment of uncertainty to be performed at the model calibration stage. Some typical measures of uncertainty might be the 95% confidence limits on flows at different lead times, or the probability distribution of flow estimates around the median value.

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. multiple stochastic runs for an integrated catchment model), 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.

The "Real Time Modelling" guidelines list the following general approaches to assessment of uncertainty:

Table 7.3 Some 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)

The assessment of uncertainty is one of the key themes in a major UK-based flood forecasting R&D programme (the EPSRC Flood Risk Management Consortium, 2003-2007) which involves many UK universities and inputs from Agency practitioners, and the outputs from this programme will no doubt improve the state of the art within the Agency in assessment of uncertainty.

Assuming that the uncertainty in forecasts can be estimated, there is then the question of how this information would be used operationally. This is particularly the case for use by staff from other disciplines who may be co-opted into flood warning only for the duration of an event. Krzysztofowicz (2001) gives an interesting discussion of these issues, with some stated advantages for probabilistic forecasts (in abbreviated form) being 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

However, clearly the ongoing research into assessing uncertainty should also address this operational dimension i.e. how can possibly inexperienced staff make use of probabilistic forecasts in a fail safe way.

7.2.2 Uncertainty in rainfall inputs

For Transfer Function models, one of the main sources of uncertainty arises from the input rainfall data. Techniques for assessment of uncertainty can range from simple adjustments to the model input data 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 and in input data (e.g. rating curve parameters). 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

More generally, the technical report associated with the “Real Time Modelling” guidelines listed the following general techniques for assessing uncertainty in input rainfall data:

- 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
- Statistical and ‘pattern recognition’ methods for predicting rainfall arrival processes and impacts on flows e.g. depth / duration / intensity / clustering / autocorrelation
- 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)
- Predicting the impact of tracking (speed/direction) and development/decay errors for individual storms
- Purely statistical sampling in which assumed autoregressive, bias and other errors are propagated through rainfall runoff models

EPSRC Flood Risk Management – Flood Forecasting Themes

From early proposals, this major UK research programme, running from 2003-07, will include the following work packages in the area of flood forecasting:

Development of uncertainty framework for flood modelling Increasing capacity is providing the opportunity for much more subtle analysis of uncer has in the past been possible in flood models. Increasingly decision makers ar information about the uncertainties and sensitivities in model predictions. Re scope the potential components of a toolkit of routines for uncertainty handlin and demonstrate key elements and implement them in an open sourc environment with the provision of an open-source toolkit.

Flood Forecasting aided by Artificial Intelligence Modern flood modelling systems involve large amounts of data, which are sourced from a variety of traditional sensors, to modern weather radar, LiDAR and satellites. Different levels of uncertainties are embedded in these data and this hampers conventional hard computing approaches that usually require detailed descriptions of the problem being solved. Artificial Intelligence or Soft Computing is an innovative approach to constructing computationally intelligent systems, which include artificial neural networks, fuzzy set theory, evolution computation (e.g. genetic algorithms), support vector machines/relevance vector machines and expert systems. This research aims to develop a methodology to deal with real time data quality, a methodology to deal with model adapting and self learning and will provide a prototype 'toolkit'.

Earth Observation and Remote Sensing in Real Time for Flood Forecasting. Despite decades of research and development on the weather radar network in the UK, the quantitative use of weather radar as an input to real time flood forecasting systems is still low and traditional raingauge networks often fail to detect severe storms. However, weather radar and raingauge data are measuring rainfall from a totally different perspective, and real time integration of these two dissimilar datasets tends to degrade their numerical integrity instead of improving it. Various approaches to the use of earth observation and remote sensing will be considered where they offer a real time application potential and particular recognition will be given to the emerging EA/DEFRA research agenda provided by TAG output.

Real Time Model Updating Real time flood forecasting systems acquire new data from a variety of sources during the progress of an event and different types of mathematical structure allow various approaches to updating the model parameters during the course of the event. This work package proposes to develop a series of approaches for abstracting the information content available in the new data for the purpose of introducing some model learning capability specifically in real time. A useful approach in other areas has been to utilise sequential estimation algorithms such as Kalman Filters for the solution of this problem. In addition the possibility exists of exploiting AI approaches. Catchment state updating will also feature.

Figure 7.1 shows some possible ways of presenting estimates of uncertainty in a real time flood forecasting system (although it should be noted that at most 1-2 of these measures would appear on the model output at any one time). Figure 7.1(a) shows multiple realisations for the model forecasts using alternative (ensemble) realisations for rainfall inputs (or forecasts) and/or for the model parameter values, whilst Figure 7.1(b) shows some classical ways of presenting information on the uncertainty in the flow estimates (confidence limits, Whisker Plots, probability distributions).

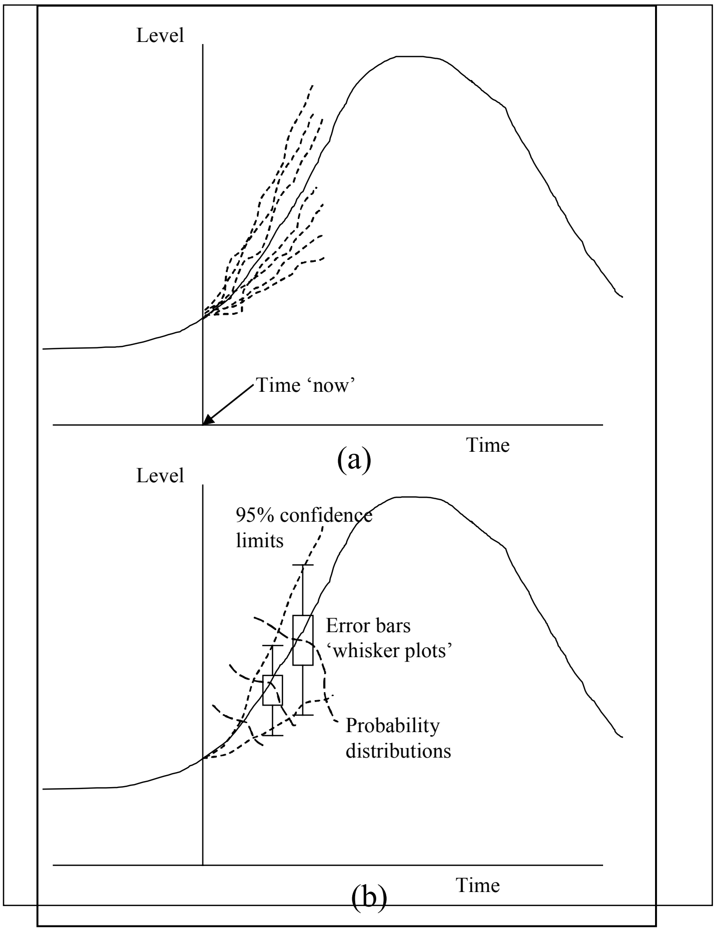

Figure 7.1 – Some examples of ways of presenting model uncertainty in real time

Although methods of this type have been used in some overseas applications, in current Agency practice, there are presently no systems which can compute or display uncertainty in real time except for the following simple approaches:

- What if simulations trying alternative (manually entered) scenarios for future rainfall operations (e.g. the WRIP system)
- Simultaneous display of hydrographs computed using radar and raingauge based rainfall estimates (e.g. in South West Region)

7.2.3 Example Applications

Due to the inherently stochastic nature of Transfer Function models, estimates can often be obtained for the uncertainty in the model parameters and flow outputs as part of the model calibration process. Also, Monte Carlo Simulation methods may be used to derive multiple alternate realisations of the model parameters based on their estimated probability distribution functions (e.g. Young, 2001). In the latter case, typically of the order 1000-10000 realisations would be used to adequately map out the distribution of output flow values and the likely envelope of maximum and minimum values at each time step.

In the case of the DBM approach, for example, the uncertainty in the estimated model is always quantified and this information can then be utilized in various ways. For instance, it allows for the application of Monte Carlo-based uncertainty and sensitivity analysis, as well as the use of the model in statistical forecasting and data assimilation algorithms, such as the Kalman Filter. The uncertainty analysis is particularly useful because it is able to evaluate how the covariance properties of the parameter estimates affect the probability distributions of physically meaningful, derived parameters, such as residence times and partition percentages in parallel hydrological pathways (e.g. Young, 1992; Lees, 2000). This approach probably represents the ‘state of the art’ in the assessment of uncertainty in Transfer Function based flood forecasting, and for the future – with appropriate software and training - presents the opportunity to provide flood forecasting duty officers with estimates for model uncertainty at each time step up to the maximum forecast lead time.

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APPENDIX A – SUMMARY OF CONSULTATIONS

During this project, the following Agency Regions and research organisations were consulted regarding recent developments in Transfer Function modelling.

Consultee	Representatives	Dates
Environment Agency Regions		
South West	Oliver Pollard	Various April-August 2003
North West	Ben Lukey, Chris Tomlin	August 2003
Anglian	John East	August 2003
Southern	Mike Vaughan	July-August 2003
Research Organisations		
Bristol University	Professor Ian Cluckie Dr Dawei Han	June 2003
Lancaster University	Professor Peter Young	June 2003

For the Agency consulations, this Appendix summarises the main findings from these consultations under the following general headings:

- History
- Types of Models
- Real Time Updating
- Model Calibration and Validation
- System Environment
- Operational Applications
- Operational Issues
- Future Development Plans

(Information obtained from research organisations appears in the main text with appropriate references).

A1. SOUTH WEST REGION

A1.1 History

The Wessex Water Authority (Somerset Division) was responsible for implementing some of the first real time Transfer Function models to be used operationally for flood forecasting in the UK (e.g. Biggs, 1980). The models used were simple Non Linear models with a variable proportional loss approach to effective rainfall estimation based on Catchment Wetness Index. Models were calibrated using a Recursive Least Squares approach with Flow Substitution updating and both catchment average rainfalls (from raingauges) or rainfall forecasts could be used to run the models.

In the early 1990s, a new run time environment called WRIP (Weather Radar Information Processor) was acquired, which was a state of the art system capable of using both weather radar and raingauge data. The PRTF formulation was also introduced at about this time. Since then, various improvements have been made to WRIP and the models that it runs so that, by the time of the Autumn 2000 floods, some 33 Transfer Function models were running on the system. In the past 2-3 years, the Region has made significant improvements both in the number of models available, and the underlying techniques and software capability as described below.

A1.2. Types of Models

South West Region currently operates only one type of Transfer Function model; the PRTF Linear Model described in Section 2.2.1. Models can be operated using estimates of catchment rainfall from raingauges obtained using a surface fitting approach, or weather radar based estimates. To date, the models used operationally have used total rainfall but trials have also been performed off-line for some sites using effective rainfall as an input. The algorithm being evaluated is based on that used in the IHACRES software discussed in Section 2.2.2.

The Regional flood forecasting system (WRIP) also includes a ‘hard coded’ integrated catchment forecasting model for the upper Bristol Avon catchment, although this has not been used operationally to date. This model was developed in the late 1990s and is of semi-distributed form, consisting of 7 PRTF function models feeding inputs into flow routing models for the main river which use a cascade of non linear reservoirs similar to the Nash cascade approach. These models sum and route the modelled inflows as appropriate.

In time series analysis jargon, the Bristol Avon model consists of single input single output (SISO) PRTF models feeding into a Multiple Input Single Output (MISO) routing model of the Multiple Genetic Linear Reservoir (MGLR) form. The MISO model parameters can be pre-defined or calibrated (i.e. updated) in real time using a least squares estimation approach solved directly using genetic algorithms which include a probabilistic element.

A1.3. Real Time Updating

In operational use, the PRTF model outputs can be adjusted by tuning the three parameters which control the shape, volume and timing of the hydrograph. 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. To help with this process, South-West Region has recently trialed a look-up table based approach linking the parameter values to Catchment Wetness Index

(CWI) as illustrated in the following table and described in more detail in Factsheet A in Appendix B.

Table A.1.1 Look up table for manual updating of PRTF models

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 this particular catchment, when the catchment is saturated in winter, and 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. The intention is that, when updating is used operationally, these volume, shape and timing values will be used to achieve the required 'tuning' of the hydrograph. However, this procedure is used manually at present so is cumbersome to apply in real time, except for key sites where the forecast is crucial (e.g. when deciding whether to issue a Major Incident Plan alert).

A1.4. Model Calibration and Validation

Current practice is to calibrate PRTF models using the MATH software which is a stand-alone package designed for use with the WRIP system (see Section 3.2.1). MATH has an easy to use graphical user interface in which a series of 'radio buttons' can be used to select the overall model structure. The optimum parameter values for that structure are then estimated using a Recursive Least Squares approach, either for the full hydrograph or for values above a user specified flow threshold. In South West Region, the optimisation criterion for automated fitting of parameters is the root mean square error (although the MATH software also calculates the Akaike Information Criterion, coefficient of determination and explained variation).

The recommended calibration sequence in the user guide is:

- Select model type: Linear Transfer Function or PRTF
- Select the orders for the flow (a_i) and rainfall (b_i) parameters and a time delay if required.
- Check the difference between the simulated (predicted) flow and actual (observed) flow
- Go to step 2 to try another combination of a and b orders
- Choose the best fit from the trials as the final solution

Following the initial optimisation, the parameter values are then adjusted manually using visually intuitive 'sliders'; for example to achieve a better match for the magnitude and timing of flow peaks (possibly at the expense of the fit to the full hydrograph). Various diagnostic plots are also available, such as the serial correlation (autocorrelation) functions for rainfall and flow, and the cross correlation coefficient between rainfall and flow (this gives a qualitative indication of typical lag times in the system and the strength of the relationship between total rainfall and flow). The model impulse response, and poles and zeroes (which relate to model stability), are also plotted as part of the calibration results.

Initially, for a given site, the model is calibrated from one event which is in-bank (hence with the rating well defined) and with the catchment saturated (so that the total rainfall is a reasonable estimate for effective rainfall). Using these parameters, the shape/volume/time delay factors are then adjusted to obtain a consistent set of parameters across several similar events for use in real time, whilst retaining a positive impulse response curve.

Within the software, the number of flow parameters is constrained to be 3 for reasons of model stability whilst the number of rainfall parameters can vary between 0 and 8. Typically, models calibrated using the MATH software have a (3,4,T) structure, although lower order models can also be derived. Alternative parameter sets may also be derived applicable to ranges of Catchment Wetness Index, or applicable to high rainfall intensities.

An effective rainfall component has recently (2003) been added to the version of the MATH software used in South West Region although is not yet used operationally. Values are calculated from the total rainfall using the IHACRES approach which requires the following user-specified parameters and input data:

- reference air temperature
- air temperature time series (hourly, daily or constant)
- catchment drying constant
- temperature modulation factor

The software then calculates an optimum value for the volume forcing coefficient in the IHACRES formulation. The option is also provided to subtract an estimated baseflow from the total flows before calibration, calculated as exponentially decaying function starting from a typical flow value before the start of the flood event, and using a user specified value for the time constant. This baseflow component – or a user specified constant flow – can be subtracted from the observed flows to derive a ‘surface runoff’ component for use with the effective rainfall values. The software allows flows calculated using both total and effective rainfall to be compared together on the screen.

A1.5. System Environment

For real time operation of Transfer Function models, South West Region uses the Weather Radar Information Processor system (WRIP) which was originally developed in the early 1990’s for the integrated display of weather radar, rain gauge and river gauging station data, and to act as a real-time forecasting platform for Transfer Function rainfall-runoff models.

The WRIP system is described in more detail in Section 3.2.1. However, it is worth noting that the version used in South West Region also incorporates the ‘hard coded’ version of the Bristol Avon model described above, and a number of improvements are scheduled for 2003 and 2004 in the areas of real time updating, effective rainfall processing and the export of forecasts to the Regional telemetry system (see under ‘Future Plans’).

A1.6. Operational Applications

At the time of the Autumn 2000 floods, some 33 Transfer Function models were running operationally in the Region and the number of calibrated models has been increased significantly since that time.

Model runs are initiated based on raingauge alarms and Nimrod/Gandolf rainfall forecasts and are event based (i.e. run on demand, not continuously). The model outputs are used as a guide to likely flooding (particularly at Major Incident Plan locations), although it is believed that no Flood Warnings have been issued solely on the basis on model outputs alone. PRTF models are now being developed for more than 85 sites in North and South Wessex Areas, and more than 50 in Devon and Cornwall Areas and Figure A.1.1 shows the locations of models which are currently operational or under development in the Region:

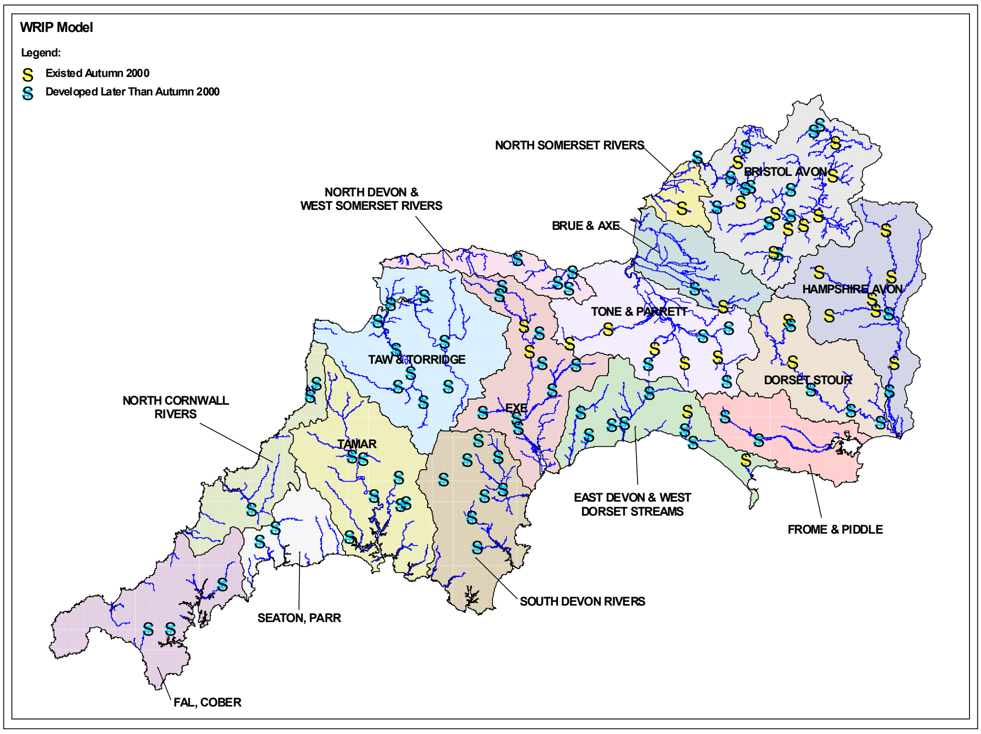


Figure A.1.1 Sites with existing or new transfer function models in South West Region (source: South West Flood Forecasting Improvements Feasibility Study, 2003)

A1.7. Operational Issues

A1.7.1 Performance Monitoring

In parallel with the recent major increase in the number of calibrated models available in the Region, a new approach to performance assessment has also been developed including contingency tables and plots summarising peak levels predicted with actual values. Although to date these methods have been applied mainly to the validation of new models, they also provide a possible framework for future performance monitoring of existing models following flood events.

The following examples show a contingency table for the Austins Bridge site (also called a correlation table in the reports) and a peak level plot.

WRIP Catchment Model Information

Catchment: Dart
Site: Austins Bridge

Model Type	B	0	L	0
Date Installed	July 2003			
Calibration rain source	Gauge			

Correlation Table: Austins Bridge (Jan. 1999 - April 2003)

DRY MODEL				**Simulated**					
Model 1 CWI < 125				No Warn	F. Watch	F. Warn	FWU	SFW	**Model Performance**
Adjustment Factors		**Actual**	No Warn	9					Good
Volume	20		F. Watch						Unknown
Shape	0		F. Warn						Unknown
Time	2		FWU						Unknown
Events	9		SFW						Unknown
							Summary		Good

For the Dry Model the minimum rainfall analysed was 30mm in 8hrs.
This would be expected to generate a Flood Wrn. on a wet catchment.

WET MODEL				**Simulated**					
Model 2 125 < CWI < 145				No Warn	F. Watch	F. Warn	FWU	SFW	**Model Performance**
Adjustment Factors		**Actual**	No Warn						Unknown
Volume	85		F. Watch			1			Unknown
Shape	4		F. Warn			8			Good
Time	1		FWU				2		Unknown
Events	11		SFW						Unknown
							Summary		Good

SATURATED MODEL				**Simulated**					
Model 3 CWI > 145				No Warn	F. Watch	F. Warn	FWU	SFW	**Model Performance**
Adjustment Factors		**Actual**	No Warn						Unknown
Volume	80		F. Watch						Unknown
Shape	0		F. Warn			4			Unknown
Time	2		FWU				1		Unknown
Events	5		SFW						Unknown
							Summary		Good

Notes:
Performance Key

Poor	≤ 50% Warnings correctly predicted
OK	50 - 75% Warnings correctly predicted
Good	≥ 75% Warnings correctly predicted
Unknown	Less than 5 events so cannot classify

Figure A.1.2 Example of a Contingency Table for Austin's Bridge on the Dart (FWU = Flood Warning Update)

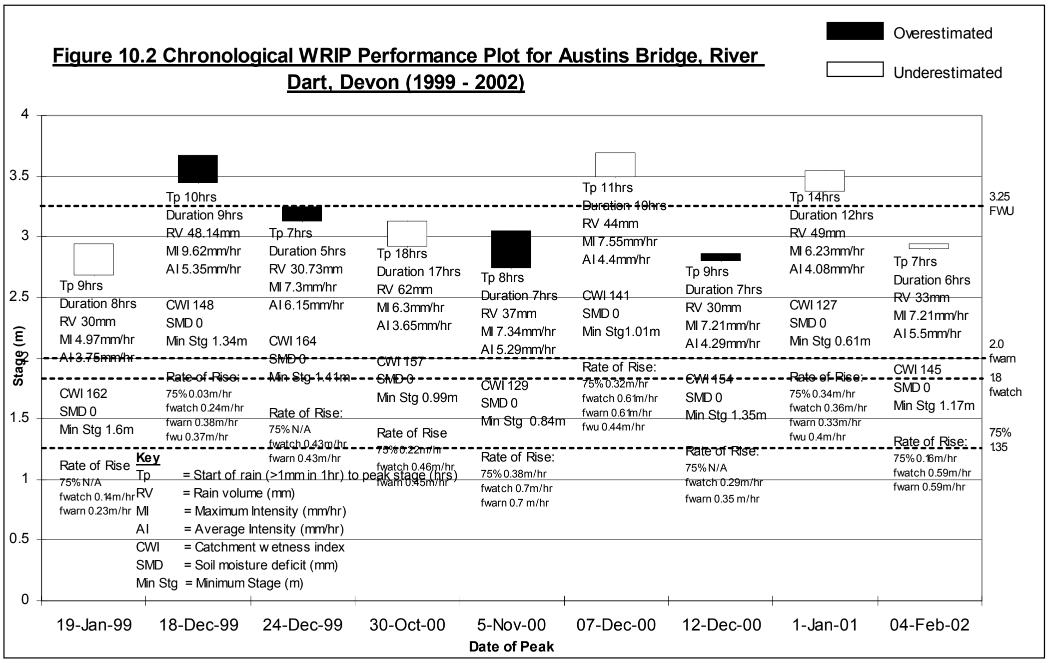


Figure A.1.3 – Example of a peak level comparison plot for Austin's Bridge on the Dart

In Figure A1.3, the black and white boxes provide a pictorial representation of the amount by which the model over or under estimates the observed peaks, whilst the tabulated information beneath these boxes summarises key statistics regarding event total rainfall, catchment state etc.

A1.7.2 Quality Assurance

For each site, Regional staff prepare a calibration report giving a brief review of the accuracy of the river level rating at high flows, current flood warning thresholds, and the model calibration. A typical report might have the following format:

- Introduction
- Hydrology
- Flood Warning
- Calibration
- Validation
- Conclusion/Recommendation

A1.7.3 Technical Expertise

The Region has at least two full time staff who have expertise in calibrating and applying PRTF transfer function models, and the various improvements to these models which are being evaluated in the Region. There are also good links with the PRTF and WRIP system developers at Bristol University and with the software suppliers who currently provide support and maintenance for the WRIP system. In recent years, all model calibration and development work has been undertaken in-house, although a consultant has worked on full time secondment since 2002 on model calibration studies. The Region also collaborates informally with North West Region (who also use WRIP) in exchanging ideas and problem solving regarding the use of Transfer Function models for flood forecasting.

A1.8. Future Development Plans

A number of improvements are planned to the existing WRIP system to deliver early improvements in flood forecasting capability in advance of implementation of the new National Flood Forecasting System (NFFS) in the Region starting from 2007. Table A.1.2 lists the main developments which are planned to the Transfer Function modelling aspects of the system.

Table A.1.2 – Planned development programme for PRTF-related aspects of WRIP

Proposed improvement	Description
WRIP system	
Real time updating of PRTF models	Feasibility study planned for 2003 evaluating the following approaches for 2 catchments (one clay and one sand dominated type): • Lancaster State Dependent Parameter • Genetic Algorithm • Volume Coefficient on CWI
Effective rainfall in PRTF models	Automated use of the IHACRES approach for estimation of effective rainfall for 2004
Radar data inputs to WRIP	Gandolf and Nimrod 1/2/5 km products available to PRTF models from 2004
Radar and raingauge inputs to WRIP	Concurrent display of radar and raingauge derived output from PRTF models for 2003

The need for regular, and systematic, performance monitoring of models has also been included as a key element for models which are used operationally.

A2. NORTH WEST REGION

A2.1. History

In the early 1990s, North West Region commissioned a new Unix-based software package developed by Salford University called WRIP (Weather Radar Information Processor). WRIP was a state of the art system supporting Transfer Function rainfall-runoff forecasting models.

Initially, WRIP was populated with approximately 20 simple Linear Transfer Function models of the type described in Appendix A.3 (Anglian Region).

Since then, WRIP has been ported to a pc-based platform and various functional improvements have been made to the software. Perhaps the most significant of these has been the option to run PRTF models in addition to Linear models.

A2.2. Types of Models

North West Region continues to operate both Simple Linear Transfer Function models and PRTF models. By the time of the Autumn 2000 floods, some 38 models were implemented on the system. In the past 2-3 years, the Region has continued to calibrate additional PRTF models for implementation on the WRIP system.

Models can be operated using estimates of catchment rainfall from raingauges obtained using a surface fitting approach, or weather radar based estimates. All new models being developed for operational use are of the PRTF type and are operated using either raingauge or weather radar based estimates (depending on the quality of data in the catchment).

To date, all models used operationally have use total rainfall rather than effective rainfall as an input although effective rainfall formulations are also being evaluated (see later).

A2.3. Real Time Updating

In operational use, PRTF model forecasts can be adjusted by tuning the three parameters which control the shape, volume and timing of the forecasted hydrograph. The aim here is to compensate for the catchment state being drier or wetter than for the events used in the original model calibration. Adjustments are made manually ‘by eye’ during the course of an event. However, this approach is presently not advised for use by MFDO’s due to the high skill level required and the uncertain results which can be obtained in some situations (with adjustments sometimes apparently making the forecasts worse).

A2.4. Model Calibration and Validation

PRTF models are calibrated using bespoke software originally developed by Salford University called MATH. MATH is a stand-alone, pc-based package designed for use with the WRIP system (see Section 3.2.1).

The package has an easy to use graphical user interface in which a series of ‘radio buttons’ can be used to select the overall model structure. The process is repeated on a trial-and-error basis for different model structures until the best (ideally, optimal) model structure is found, as judged on the basis of: (i) error statistics computed from a reconvoluted flow time series; (ii) the model impulse response, and (iii) a visual assessment of observed and reconvoluted time series.

The evaluation statistics include the Akaike Information Criterion (AIC) and root mean square error (RMSE). The parameter values can also be adjusted manually using visually intuitive ‘sliders’; for example to achieve a better match for the magnitude and timing of flow peaks (possibly at the expense of the fit to the full hydrograph).

For each model, Regional staff or their consultants prepare a calibration report describing the rating curves used (accuracy etc), the results for the selected calibration events, and any issues with the model calibration. Some proposed approaches to calibration have included averaging parameters across each calibration event (not used), and the currently adopted approach of identifying one or more sets of parameters which provide a reasonable fit across a number of similar events with similar ranges of Catchment Wetness Index (and possibly rainfall intensities).

Typically, the most recently developed models have had a (3,4,T) structure, although this is not fixed and lower order models can also be obtained (see later).

MATH models are based on quick run-off (i.e. total flow less a baseflow component, defined as the lowest flow in the calibration sequence), so the baseflow must be added back in operational (real time) use.

A2.5. System Environment

For real time operation of Transfer Function models, North West Region uses the Weather Radar Information Processor system (WRIP) which was originally developed by the University of Salford in the late 1980s (and subsequently the University of Bristol) for the integrated display of weather radar, rain gauge and river gauging station data, and to act as a real-time forecasting platform for Transfer Function rainfall-runoff models. The WRIP system is described in more detail in Section 3.2.1).

A2.6. Operational Applications

A mid 2001 estimate, using data obtained as part of preparation of the Agency’s “Real Time Modelling” guidelines (Environment Agency, 2001b) suggested that the North West Region currently has approximately 40 Transfer Function models calibrated for operational use. The locations of these models, and the model structures, are shown in Table A21. It can be seen that the majority of models have a (1,3,T) structure, and none has a structure higher than (2,3,T).

Table A.2.1 – Mid 2001 estimate for the numbers of calibrated transfer function models in North West Region

Location	Model Structure	
	m	n
Greenholme	1	3
Great Corby	0	3
Udford	1	3
Temple Sowerby	1	3
Kirkby Stephen	1	3
Sheepmount	1	3
Cummersdale	1	3
Dacre Beck	1	3
Sprint Mill	1	3
Victoria Bridge	1	3
Skerton	1	3
Killington	1	3
Hornby	1	3
Caton	1	3
Galgate	1	3
Abbeystead	1	3
Scorton	1	3
St Michaels	1	3
A6 Road Bridge	1	3
Garstang Pumping Station	1	3
Reedyford	1	3
Jumbles Rk	1	3
Oxford Road	1	3
Ewood	1	3
Croston	1	3
Central Park	1	3
Low Moor	1	3
Kirkby	1	3
Stubbins	1	3
HAN Blackford	1	3
Bury Bridge	1	3
Manchester Racecourse	1	3
Broomstaqis	1	3
Compstall	1	3
Brinksway	1	3
Marple Bridge	2	3
Causey Bridge	1	3
Rochdale ETW	1	3

Several new PRTF models have also been calibrated for that time; for example, for key risk areas (e.g. in the towns of Congleton and Blackburn).

At present, only the models for Wigan, Ewood and Congleton appear in Flood Warning Procedures as a possible source of information for MFDO's, with a further 4 models highlighted as 'possibly useful' during a flood event. The 3 operational models have two sets of parameters available, for use on a 'wet' or 'dry' catchment.

A2.7. Operational Issues

A2.7.1 Performance Monitoring

Figure A.2.1 shows a flow chart summarising the decision making process on whether a post event analysis of model performance is required following a flood event.

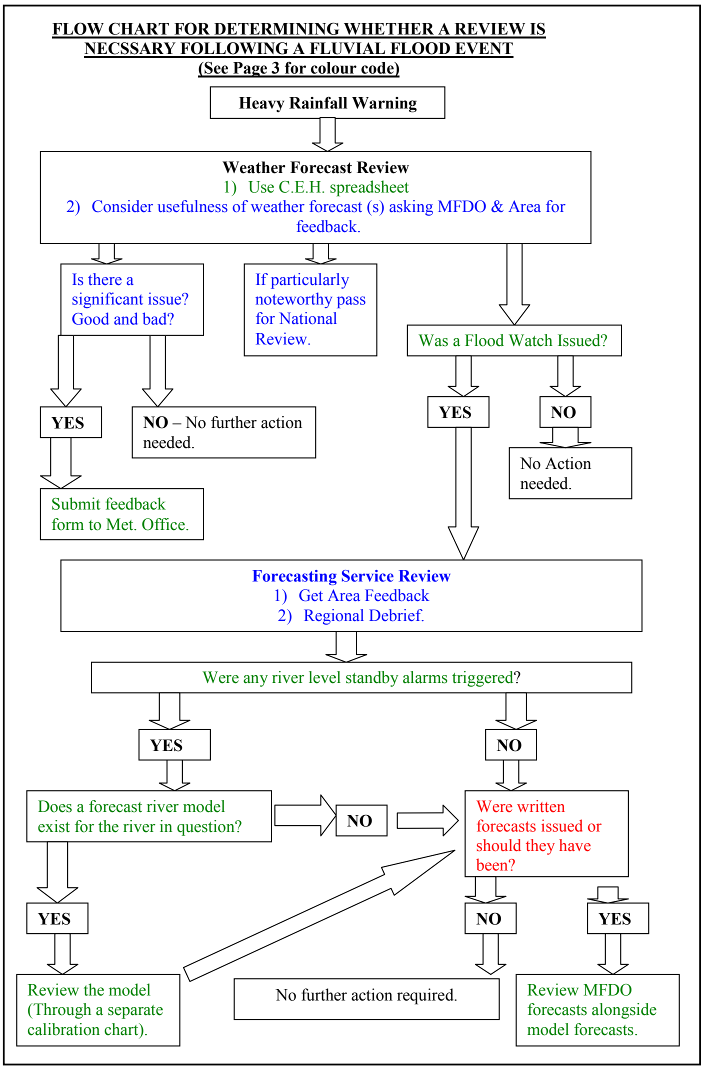


Figure A.2.1 – Flow chart for determining whether a review is necessary following a fluvial flood event

A2.7.2 Quality Assurance

A modelling specification (or brief) is currently under preparation to help ensure that all models are developed to the same standard and targets.

A2.7.3 Technical Expertise

North West Region has several staff developing skills in the calibration and development of Transfer Function models, under the guidance of one staff member who recently completed a PhD at Lancaster University in Non Linear Transfer Function models.

The Region has good links with Bristol and Lancaster Universities and also participates in an informal collaborative arrangement with South West Region to facilitate knowledge/experience sharing. Consultants with the required expertise are also used to perform calibration studies for new models for additional sites.

A2.8. Future Development Plans

North West Region is continuing to calibrate PRTF models for new high risk locations, much of which is outsourced to consultants. The version of WRIP used in the Region is also being updated so that it will calculate Catchment Wetness Index (CWI) values automatically and allow selection of model parameter sets based on CWI.

The Region also recently evaluated the Non Linear DBM models developed by Lancaster University's Centre for Research on Environmental Systems and Statistics. However, since this type of model differs in structure to the PRTF models, it cannot yet be run in real time on the WRIP platform, so this modelling work is only being undertaken off-line. Conceptual rainfall runoff models are also under evaluation.

A3. ANGLIAN REGION

A3.1. History

Anglian Region has been using Transfer Function models for flood forecasting applications since the early 1990s. The models were initially developed by Salford University as part of the Anglian Region Information Project (ARIP).

A3.2. Types of Models

The models used are Linear Transfer Function Models using total rainfall as an input. The models are operated on an hourly basis and are of the form:

$$Q_t = a_1 Q_{t-1} + a_2 Q_{t-2} + \ldots + a_m Q_{t-m} + \delta\,(b_1 R_{t-T} + b_2 R_{t-1-T} + \ldots + b_n R_{t-n-T}\ )$$

where:

Q = fast response flow
R = rainfall
$a_1, a_{2 \ldots} a_m$ = the model's flow parameters
$b_1, b_2 \ldots b_n$ = the model's rainfall parameters
T = an optional time delay

The parameter δ is related to the percentage runoff, and can be updated at every time interval. The models are used on an event basis.

The model is formulated in terms of fast response flows and estimated baseflow must be added to the results to obtain the total flow (usually taken as the antecedent flow before commencement of the event).

Also, for many sites, two parameter sets are derived, corresponding to the average runoff response and a fast response. In real time operation, model users then select the most appropriate model on the basis of antecedent conditions and the observed response during the current event.

Although this form of transfer function model was originally developed for use with a catchment average rainfall input derived from weather radar, these operational models use total rainfall as estimated from telemetered raingauge data using predefined weighting factors (e.g. Thiessen factors) for each of the raingauges associated with a given model.

A3.3. Real Time Updating

Models can be updated automatically using the parameter δ in the equation above. The software automatically compares observed and forecast flows up to time now, and provides a best estimate for δ based on this comparison at each hourly timestep. Small or zero variations over time in this parameter provide an indication of a model with good predictive capability. Constraints are imposed to limit the size of any change in δ from one time step to the next thereby prevent instability in the updating.

However, experience in the Region using this automated approach has sometimes resulted in poor forecasts therefore the factor δ is now fixed for each forecast run. The general procedure is to match forecast and observed flows as best as possible by trial and error adjustment of δ or selection of a fast response model.

A3.4. Model Calibration and Validation

Models can be calibrated using two software packages developed by the University of Salford (called TFCAL and TFUH). TFCAL estimates the model parameters in a conventional manner from rainfall and flow time series; THUH is less conventional in that the transfer function parameters are estimated from unit hydrograph ordinates – this procedure was developed due to the large number of unit hydrograph models that had been developed for Anglian Region up to the late 1980's.

The calibration software limits the structure (order) of models to a maximum of 6 flow parameters, 6 rainfall parameters, and a maximum time delay of 6 times the model time step, (i.e. 6 hours). The software also imposes the additional constraints that the sum of the flow parameters must exceed zero, and the sum of the rainfall parameters must be less than 1.0. At the start of the calibration process, a recommended range for δ is computed, such that the upper limit corresponds to a runoff of 100%.

A3.5. System Environment

For real time operation of Transfer Function models, Anglian Region uses an in house PC based software package which interfaces to the Regional telemetry system. The telemetry system 'pushes' the required data to the forecasting models at hourly intervals.

The software is written in the Quick Basic programming language and can display observed rainfall and flows, and forecast flows, together with flood warning thresholds, and the time series of differences between observed and forecast flows. Observed and forecast levels and flows can also be tabulated together with the observed rainfall data.

These systems are now nearing the end of their operational life and discussions are currently underway on whether to migrate the models to the Anglian Flow Forecasting and Modelling System (AFFMS).

A3.6. Operational Applications

Transfer Function models have been developed for 24 sites in the Northern Area of Anglian Region. Models are run at an early stage of a flood event, on an event basis, as tributary flows start responding to rainfall. The model forecasts provide supplemental information to help in deciding whether to issue a flood warning although the primary decision is invariably based on observations, rather than forecasts. Model users can select either the updated results or a fast response model.

It is important to be aware that the range of flow measurement at the site is a limiting factor. If actual flows exceed the upper limit of the rating then the forecast is considered invalid. Also the forecast level is invalid if forecast flows exceed the upper limit of the rating.

A3.7. Operational Issues

A3.7.1 Performance Monitoring

No formal post event or long term performance monitoring of models is believed to be performed at present although the initial model calibrations are documented.

A3.7.2 Quality Assurance

Not known.

A3.7.3 Technical Expertise

At least one staff member has expertise in use of the calibration software and several with operation of the forecasting models.

A3.8. Future Development Plans

Little development of these models is proposed in the near term although discussions are currently underway on whether to migrate the models to the Anglian Flow Forecasting and Modelling System (AFFMS).

A4. SOUTHERN REGION

A4.1. History

Southern Region has been using Transfer Function models since 2000. The models are of a simple Non Linear type and are operated within the Regional flood forecasting system (FFP).

A4.2. Types of Models

The Transfer Function models used in Southern Region are a simple version of the Lancaster DBM model:

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

where:

Q = flow
u = effective rainfall
$a_1, a_2 \ldots a_m$ = the model's flow parameters
$b_1, b_2 \ldots b_n$ = the model's rainfall parameters

The models have no time delay included. Following the DBM approach, effective rainfall is related to a function (in this case a power law function) of flows at the previous timestep i.e. $u_t = r\,(Q_{t-1})^n$

A4.3. Real Time Updating

Although the Regional forecasting system (FFP) has the capability to host models with real time updating routines (e.g. ARMA error prediction methods), it is believed that the Transfer Function models are presently operated in an 'open loop' simulation mode i.e. without updating.

A4.4. Model Calibration and Verification

Calibration and verification of the models was outsourced and it is not known what procedures or calibration software were used.

A4.5. System Environment

For real time operation of Transfer Function models, Southern Region uses the FFP software (Flood Forecasting Platform). This system operates on personal computers linked to a telemetry server, and was developed specifically for the Region by Water Resources Associates.

FFP can support other types of forecasting models including conceptual rainfall runoff models (the CEH Probability Distributed Model; PDM) and flow routing models (the CEH Kinematic Wave model; KW). Models can be operated either singly or combined into networks. The system is used for running forecasting models for a number of watercourses in Sussex and Hampshire.

A4.6. Operational Applications

Transfer Function models have been implemented on the Regional forecasting system (FFP) for the following sites:

- Iping Mill
- Westbourne
- Leigh Park
- Romsey
- Millbrook
- Horton
- Cowbeech
- Stilebridge
- Uckfield
- Isfield

From an example provided (for Westbourne), the models are of low order, with the Westbourne example being of order (2,1,0).

A4.7. Operational Issues

A4.7.1 Performance Monitoring

Not known.

A4.7.2 Quality Assurance

Not known

A4.7.3 Technical Expertise

Not known

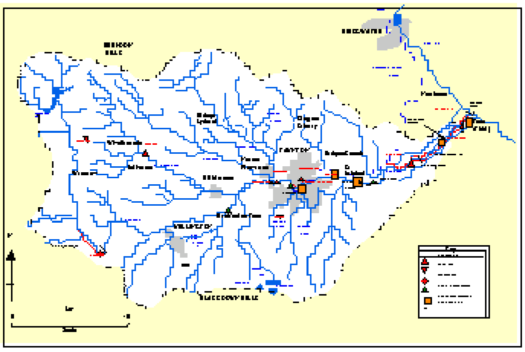
A4.8. Future Development Plans

Not known.

APPENDIX B – Model Application Factsheets

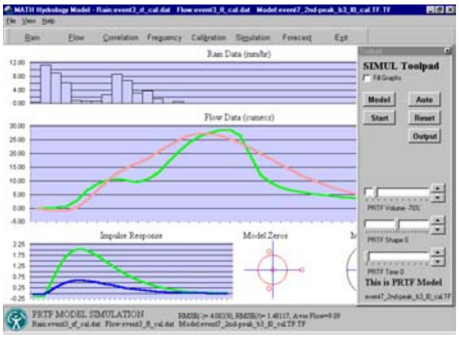
South West Region: River Tone

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.

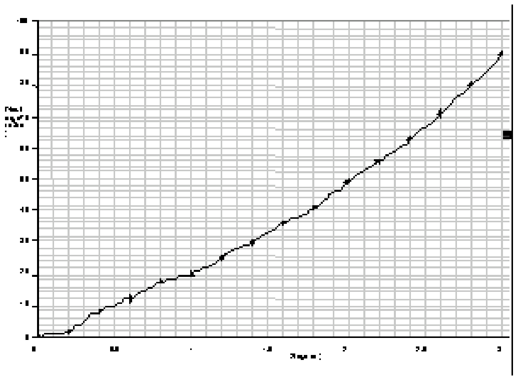


A PRTF rainfall-runoff model has recently been developed which simulates flows to Bishops Hull gauging station upstream of Taunton. The volume, shape and lag parameters of this model can be manually updated either prior to the onset of an event or during an event, and guidelines are being developed to relate these parameters to antecedent catchment conditions to objectify model initialisation. Investigations are also being undertaken to assess the impact of the use of effective rainfall on flow forecasts and on methods of defining effective rainfall.

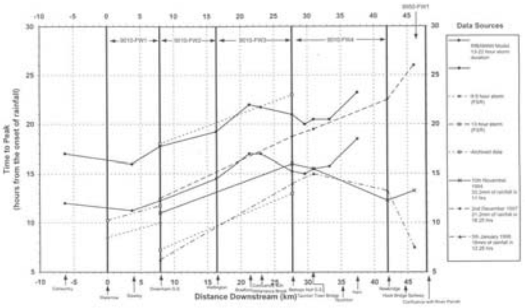
The simulation of an event on the 19th September 1999 is shown in the following figure (observed flow in green/dark grey, and simulated in red/light grey).



The flow at Bishops Hull is converted to a flood level using the ratings 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.

Recent Developments

One 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:

$$Q = 2298 Q_{t-1} - 1.760 Q_{t-2} + 0.449 Q_{t-3} \\ - 0.124 R_{t-2} + 0.163 R_{t-3} - 0.057 R_{t-4} + 0375 R_{t-5}$$

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
<50	15	-70	0	0
50-100	25	-50	0	0
100-125	35	-30	0	0-1
125-140	43	-15	0	0-1
>140	100	0	0	0

North-West Region: River Greta

A PRTF model was developed in 2001 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 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 model was calibrated using the MATH package and (3,2,2) and (3,2,1) models were evaluated, with the latter giving the best fit. The form of the calibrated model is:

$$Q_t = 2.319 Q_{t-1} - 1.793 Q_{t-2} + 0.462 Q_{t-} \\ - 0.160 R_{t-2} + 1.182 R_{t-3} - 0.737 R_{t-4}$$

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.

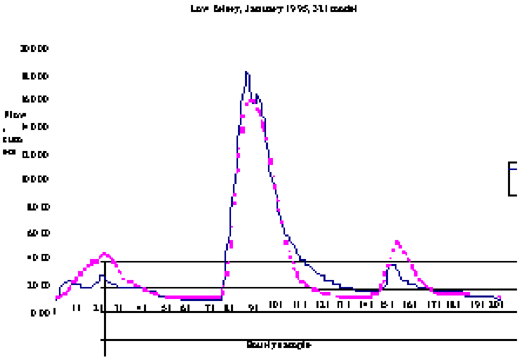
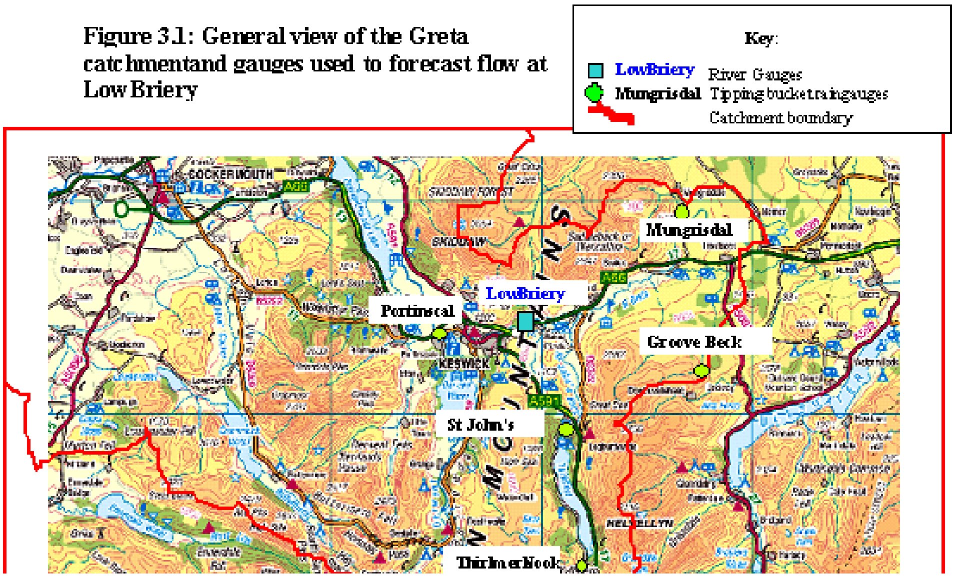


Figure 3.1: General view of the Greta catchment and gauges used to forecast flow at Low Briery



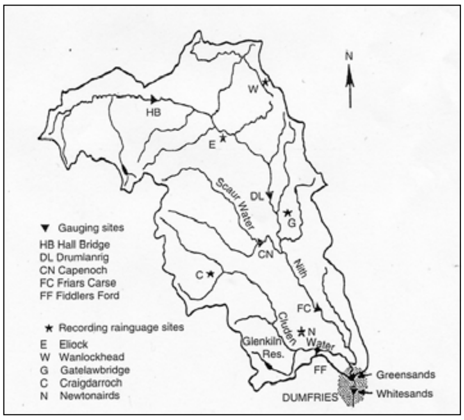
SEPA: Dumfries Flood Forecasting Model

The town of Dumfries lies on the River Nith, which has a catchment area of 1112km^2 at Dumfries. Average annual rainfall increases from less than 1000mm around the Nith estuary to over 2000mm in the upper parts of the catchment where several peaks rise to an altitude of 650m.

A flood forecasting system was established for the lower part of the catchment in 1991 incorporating both rainfall runoff and flow routing Transfer Function models (Lees et al., 1994; Beven, 2000; Younger, 2003). When implemented, the catchment had 3 tipping bucket raingauges and 6 river level recorders on telemetry. One novel feature of the design was that the system should automatically send computer generated messages to the police, who had responsibility for issuing flood warnings at that time. Also, since there are tidal influences in the lower parts of the town, a Transfer Function modelling approach was also used to estimate the influence of the tides on water levels in the Nith.

The models used were an early version of the Data Based Mechanistic (DBM) type and were typically of structure (1,1,T). The routing and tidal (estuary) models were formulated in terms of stage, as was the rainfall runoff model for the main tributary in the lower reaches (Cluden Water).

Real time updating was implemented in the form of an Adaptive Gain approach incorporating a slowly varying random walk process. The recursive estimation approach also allowed the variance of the forecasts to be estimated, providing a measure of forecast uncertainty in real time.



The original specification for the model was for a minimum of a 5 hour lead time for forecasts, which is beyond the natural lag time of the catchment in the lower reaches. A pragmatic approach was adopted in which an artificial time delay was introduced to extend the forecast lead time, with the models calibrated to include this delay (in effect introducing a crude form of forecasting assuming persistence in rainfall and flows). Although the model fit was not as good as for the 'natural' time delay, the performance was still acceptable, and greatly improved when updating was in operation.

Operational experience with the model has been good; for example predicting the peak stage to within 0.05m for two events which caused flooding in Dumfries in 1991 and 1993, and with only small errors in timing (although recent operational experience has suggested that the model requires recalibration to take account of changes in catchment response etc since its original development).