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Flood and coastal erosion risk management
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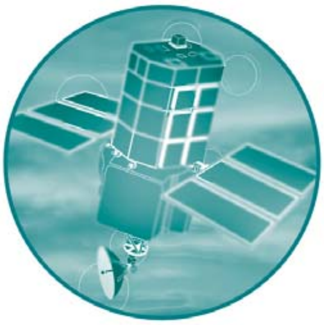

Protocols For Minimum Standards In Modelling

Flood Warning Management System Phase 2a

R&D Technical Report W5C-021/2a

Department for Environment
Food and Rural Affairs

ENVIRONMENT AGENCY

Protocols for minimum standards in modelling

(Flood Warning Management System Phase 2a)

R&D Technical Report W5C-021/2a

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Statement of Use
This report, which constitutes an output from the Joint Defra /Environment Agency Flood and Coastal Defence R&D Programme, describes a set of generic protocols intended to promote the achievement of minimum standards in modelling for real-time flood forecasting. The Protocols cover key technical issues in model design, build, calibration and testing and are to be applied as a series of retrospective checks ensuring that necessary benchmarks have been met.

Keywords
Fluvial flood forecasting, real-time modelling, minimum standards, quality assurance.

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FOREWORD

The authors would like to thank the Project Board (Rahman Khatibi, David Hill, Oliver Pollard and Nigel Outhwaite) for their technical input throughout this R&D project. We gratefully acknowledge all Agency staff that contributed including Doug Whitfield, Shirley Greenwood, Richard Cross, Kate Scott, Richard Knight, Gavin Sharpin, Ian Pearce, Mike Vaughan and Dan Cadman. Special thanks to Katherine Self, Ali Asghar Akhondi-Asl and Jonathan Coulby of North East Region's Flood Forecasting team for their time spent explaining the operation of the RFFS and NFFS to us.

We would also like to thank the following individuals and organisations who kindly gave their time to respond to consultation during the project: Chris Whitlow (Eden Vale Modelling Services), David Stark (Jacobs Gibb), David Worth (Haskoning UK), Jenny Pickles (Bullen Consultants), Adrian Philpott and Kevin Sene (Atkins) and Peter Hawkes (HR Wallingford).

EXECUTIVE SUMMARY

The National Flood Forecasting System (NFFS), currently being deployed within the Environment Agency, is an open architecture system for flood forecasting which enables many different types of model to be combined and run concurrently. This will allow users much greater flexibility as to the modelling approach and type of model they choose when developing new forecasting models or upgrading existing ones.

To safeguard against business risks associated with this increased flexibility, the Agency has developed guidelines for best practice in flood forecasting in real time as well as more prescriptive specifications for particular models or modelling software. However, a requirement for generic methods of model evaluation and assurance has also been recognised. For example, specifying minimum standards or benchmarks for modelling that are applicable for all model types/approaches would help to ensure that all models being incorporated into NFFS pass some threshold of acceptability.

This project, W5C-021 (Part 2a), has been promoted by the Flood Forecasting and Warning Theme Advisory Group of the joint Defra/EA Flood and Coastal Erosion Risk Management Research Programme to create generic ‘protocols’ initiating minimum standards in development of river models for real time forecasting. The Protocols take the form of a series of statements, backed up by ‘checklist’ questions that can be used at various stages within a modelling project to provide a documentary record of compliance with an agreed minimum standard. The Protocols presented in this report are structured to fit in with a proposed modelling strategy, supported by an Outline Modelling Specification for Flood Forecasting.

Consultation carried out in the course of this project revealed general support for some consistent system for quality assurance of forecasting models, but little consensus as to the need or form of the protocols envisaged in the original brief for the R&D. Concerns included the appropriate level of detail and the risk of creating additional ‘red tape’ for experienced professionals. The Protocols have therefore been drafted with the requirement for minimum standards in mind, rather than being regulatory in nature. The emphasis in their use should be on providing consistent documentation of modelling work to avoid any sense that the Protocols are seeking to impose restrictions on the solutions adopted by informed modelling teams.

An interactive Word proforma for documenting the Protocols has been developed as an additional output of this project.

CONTENTS

LIST OF ABBREVIATIONS

1-D, 2-D	One dimensional / two dimensional
Agency, EA	Environment Agency / Environment Agency Wales
CFMP	Catchment Flood Management Plan
FDMS	Flood Defence Management System (now replaced by NFCDD)
FDO	Forecasting Duty Officer
GMS	Generic Modelling Specification
JBA	JBA Consulting Engineers and Scientists
NFCDD	National Flood and Coastal Defence Database
NFFG	National Flood Forecasting Group
NFFMS	National Flood Forecasting Modelling Systems Strategy
NFFS	National Flood Forecasting System
NFWC	National Flood Warning Centre
OMS	Outline Modelling Specification
RFFS	River Flow Forecasting System
RMSE	Root Mean Square Error
SFRM	Strategic Flood Risk Management
ToR	Terms of Reference

1 INTRODUCTION

1.1 Background

The National Flood Forecasting System (NFFS), currently being deployed within the Environment Agency, is an open architecture system for flood forecasting which enables many different types of model to be combined and run concurrently. This will allow users much greater flexibility as to the modelling approach and type of model they choose when developing new forecasting models or upgrading existing ones.

Unfortunately this increased flexibility and choice may also lead to less consistency in approaches and standards of modelling between different personnel, different consultants and different regions of the Agency. One safeguard against this business risk has been the development of guidance on best practice in flood forecasting and river modelling in real time through research and development projects. A second strand has been provision of prescriptive guidelines for particular models or modelling software.

However, a requirement for generic methods of model evaluation and quality assurance has also been recognised. For example specifying minimum standards or benchmarks that are applicable for all model types / approaches, would help to ensure that all models being incorporated into NFFS pass some threshold of acceptability. Such a scheme would also contribute towards creating transparency in modelling practice and help to ensure efficiency when modelling components are changed in future, or when personnel changes occur.

The Environment Agency therefore established this R&D Project, W5C-021 *Protocols for Minimum Standards in Modelling* (Flood Warning Management System Phase 2a), to develop 'Protocols' that will enable both modellers and project managers to demonstrate that required milestones have been passed during the various stages of the modelling process. The project has been commissioned within the Flood Forecasting and Warning Theme of the Defra / EA Joint Thematic R&D Programme for Flood and Coastal Defence. The Environment Agency Science Group project code was SC020076.

1.2 Concept of Protocols for minimum standards in modelling

1.2.1 Scope and definition

The project brief did not specify a particular form or format for the 'Protocols'. The scope of the project was therefore established in discussion with the project board, and through a consultation process with modellers (including both consultants and Agency staff). Based on these discussions it was agreed that the Protocols should:

- be developed as a short list of statements that can be accepted or rejected to indicate whether or not modelling work has reached a certain minimum standard (agreement with the statements is decided by answers to a set of supporting questions),
- be tailored to the main stages that are undertaken when building a forecasting model for real-time use,
- demonstrate that a minimum standard has been achieved before work progresses to further stages, and

- be primarily designed for use with models of fluvial flooding.

However, it was also agreed that the Protocols should not explicitly test the validity of the selected modelling approach, as such considerations are addressed in existing technical guidance.

1.2.2 Role of Protocols in the context of a flood forecasting modelling strategy

Figure 1.1 illustrates the intended role of the Protocols within the Agency's proposed approach to quality assurance and audit of modelling practices in its flood forecasting business (focussing on fluvial flooding). They are to be applied as retrospective checks at each main stage of the model building and testing cycle (here shown as consisting of five stages), ensuring that key tasks have been undertaken with adequate care and consideration, and that outputs are valid and properly documented.

The users of the Protocols will be both the various modelling teams in the Agency and its modelling consultants, i.e. applying the Protocols is likely, in practice, to be a modelling activity, but 'signing them off' will be a management activity.

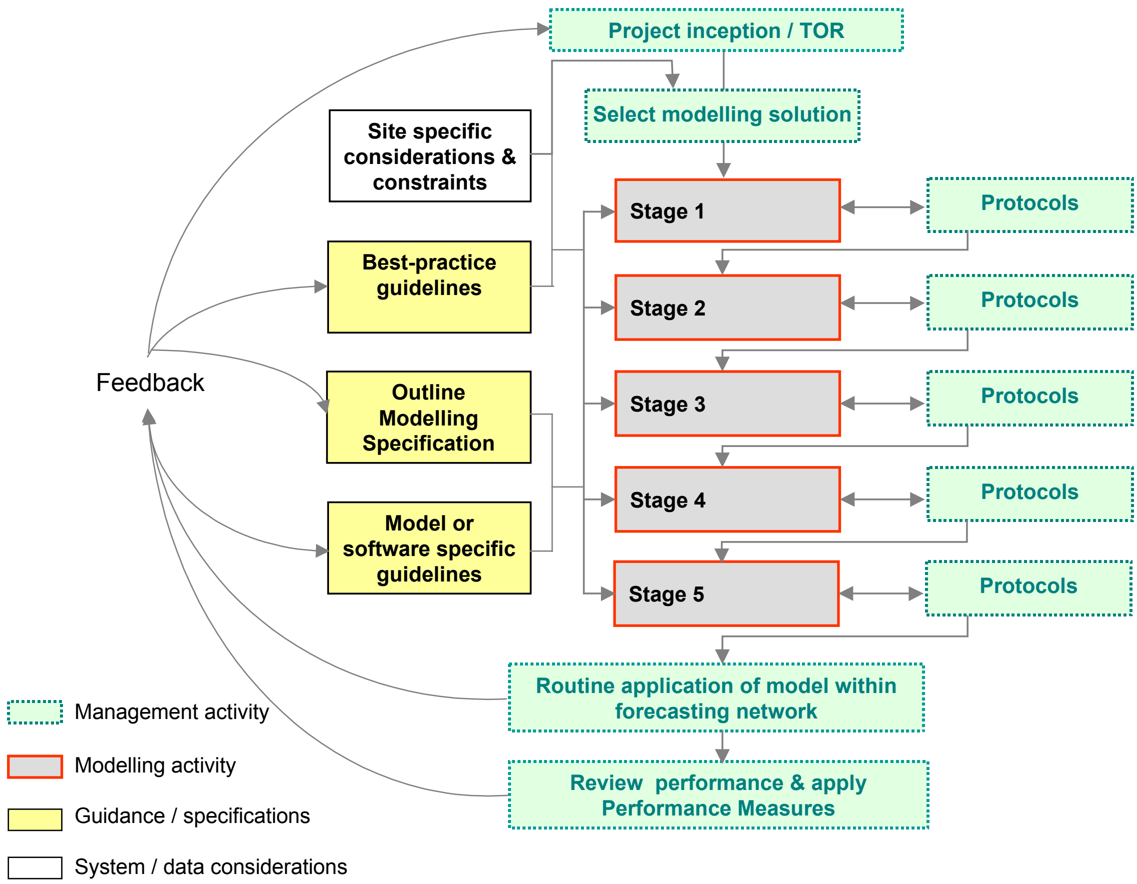

Figure 1.1: Modelling strategy for fluvial flood forecasting – generic outline

1.2.3 Related approaches to quality assurance

As shown in Figure 1.1 the Protocols are not the only aspect to this strategy, and there are a number of other elements to it that are currently being (or have been) addressed by related R&D projects (discussed further below). These include:

(i) Provision of guidance and specifications for developing flood forecasting models for use in real time. This guidance may be further categorised into four main types:
- documentation of best practice in flood forecasting and warning,
- technical guidance on selection of appropriate modelling approaches / solutions,
- technical specification for fluvial flood forecasting models (Outline Modelling Specification), and
- model or software specific guidelines / codes of practice.

(ii) Performance Measures for evaluating the routine application of the forecasting model.

Best practice documentation / technical guidance
Best practice documentation providing technical guidance on model selection has been provided by a number of recent R&D outputs including the Baseline Review (Defra/EA, 2002), a review of model selection issues for real time modelling reported by Tilford *et al*. (2003) and reviews of best practice in coastal (Defra/EA, 2003) and estuarine (Harpin *et al*., 2002) flood forecasting. These studies are discussed further in Section 2.2. As model selection issues are already covered in detail by these existing reports, the Protocols are not explicitly intended to address them.

Outline Modelling Specification for Flood Forecasting
The Outline Modelling Specification (OMS) for Flood Forecasting is a technical specification that outlines, at a generic level, the activities and considerations required at each stage in the process of building and testing a flood forecasting model. The aim of the OMS is to provide a formalised, consistent and structured methodology to which the modeller can work, which is independent of model type.

A definitive version of the OMS has been prepared in line with the Protocols and is included as an Appendix to this report. It is based on previous generic modelling specifications used within the Agency (e.g. Cadman, 2002) but has been adapted to focus on forecasting models for fluvial flooding.

Model / software specific guidance
Guidelines that assist modellers to prepare hydrodynamic flood forecasting models using Isis software are currently being circulated to the Agency's consultants. These give specific instructions on putting together model datasets to optimise their use within NFFS.

Performance Measures R&D
A project to develop 'generic performance measures' is being undertaken by HR Wallingford Ltd. It is running separately to, but in parallel with this project (project code W5C-021-2b), but whilst the aim here is to create minimum standards in modelling for the stages from model inception through to testing in an emulated real

time environment, the generic performance measures will assess the performance of forecasting models in actual real time applications.

Feedback
Feedback is a major element in the flood forecasting modelling strategy. It involves learning from experiences and updating guidelines and specifications as the knowledge base increases. At present there is no formalised procedure for incorporating feedback, and this is something that the Agency will address in the near future.

1.2.4 Definition of the model building and testing cycle

The model building and testing cycle (the 'modelling procedure') is central to modelling practice, as illustrated in Figure 1.1. The Protocols and an Outline Modelling Specification are both closely aligned to this cycle, and therefore defining the key stages within it is important. In particular these need to be common to all modelling approaches, i.e. whilst the development of a hydrodynamic model will be inherently more involved than one based on level correlation techniques for example, it should be possible to define a broad sequence of modelling tasks that is applicable in both cases. The National Flood Forecasting Modelling Systems Strategy (NFFMSS), as discussed by Parsons Brinkerhoff (2001), suggested that the modelling process might broadly consist of the following five key stages, which would map onto Figure 1.1:

- Stage 1 'inception',
- Stage 2 'review',
- Stage 3 'validation',
- Stage 4 'testing',
- Stage 5 'application'.

This project evaluates, through consultation, how accurately this reflects modelling projects in practice, and the need for revision.

1.3 Project objectives, management and programme

1.3.1 Aims and objectives

The main objectives of the project were to:

- review available good practice guidance,
- identify the key stages of the workflow in a forecasting modelling project,
- review and update the Agency's generic modelling specification setting out the main tasks required with each stage of modelling project,
- consult with modellers (both Agency and consultants) and Agency project managers on actual current practice and requirements for protocols,

- develop a set of protocols, and
- illustrate the use of the protocols with case studies.

Initial consultation with the project board and others confirmed that the protocols should be designed to promote achievement of common minimum standards in modelling (in other words, the protocols are not meant to be exhaustive and projects may exceed the minimum standard).

The modelling protocols should be geared towards modelling for real-time flood forecasting, although some checks may be generic in nature, and should cover key technical issues in model build, calibration, validation, sensitivity and robustness.

The protocols were not required to provide formal guidance or direction regarding model selection, or to assess the performance of a model or forecasting network in routine real time application (this is the role of the Performance Measures for Flood Forecasting R&D project). Methods for checking accuracy, quality or availability of input data were also not part of the project brief, but checks on the computational robustness of a model in the light of possible corrupted or missing data are considered.

1.3.2 Project management and programme

The Environment Agency's project manager for this project was Andrew Grime of Weetwood. The project board members were as follows:

- Tony Andreyweszki – Environment Agency (North East Region, Project Executive),
- Rahman Khatibi – Environment Agency (Head Office),
- David Hill – Environment Agency (North East Region),
- Oliver Pollard – Environment Agency (South West Region),
- Nigel Outhwaite – Environment Agency (Head Office).

The project was split into two phases. The first phase involved a review of available guidance on modelling and the consultation exercise. The findings of these tasks were presented in a Position Paper, which was subsequently discussed during a project board meeting. A programme of work for the second phase was then agreed, with the protocols to be finalised and reported. It was also agreed that the revised OMS should be delivered as an appendix to the final report.

1.4 Report structure

This report is the final technical report for R&D W5C-021-*Protocols for Minimum Standards in Modelling.* Following this introduction, Chapter 2 summarises the review of existing guidance on modelling for flood forecasting, whilst the Consultation Exercise is reported in Chapter 3.

A review of key milestones within the modelling process is presented in Chapter 4, whilst the series of protocols that have been developed are presented in detail in Chapter 5.

Two case study applications of the Modelling Protocols are reported in Chapters 6 and 7. The first example is based on a modelling project commissioned by North East Region of the Environment Agency, in which the objective was to produce a real time hydrodynamic model of the Yorkshire Ouse. The second example is a project commissioned by North West Region, in which hydraulic and routing models originally constructed for flood risk mapping studies were used to develop a real-time flood forecasting capability for the River Eden at Carlisle. In both cases the modelling was carried out by a consultant rather than 'in house'. It should be noted that neither of the case studies reported here represent a true test of the Protocols, as in each case the Protocols were assessed posthumously, rather than at each stage in the modelling project.

Summary and recommendations regarding implementation of the Protocols are given in Chapter 8.

The questionnaire distributed as part of the Consultation Exercise, a glossary of flood forecasting terms, and the Outline Modelling Specification for Flood Forecasting are included as appendices to the main report.

1.5 Other Outputs

An interactive proforma for documenting the Protocols has been developed in Microsoft Word as an additional output of this project.

2 BRIEF REVIEW OF GUIDANCE ON MODELLING FOR FLOOD FORECASTING

2.1 Sources of guidance

Whilst the Protocols should reinforce the main issues raised in relevant guidelines, it is not the intention that the Protocols should duplicate or repeat material given elsewhere. The aim of this chapter is therefore to summarise the sources of guidance that should be used independently of the Protocols.

The suite of R&D recently commissioned by the Environment Agency provides the most up to date guidance on flood forecasting in a UK context. This guidance was described briefly in Chapter 1 and is discussed further in Section 2.2. However there are several other sources of guidance on procedures for modelling that have some relevance to flood forecasting:

- The Agency's Specification for Flood Risk Mapping (widely known as the "S105 Specification") also provides useful guidance building river models. Although it is geared towards models used for mapping (sometimes referred to as "planning" or "design" models), it is also relevant to forecasting models in that it specifies good practice and certain standards for river modelling as discussed in Section 2.3.

- The Agency has recently commissioned guidelines relating to modification of S105 models developed using ISIS software for use in real time. These are discussed further in Section 2.4.

- The HarmoniQuA initiative, which outlines best practice for hydrological modelling. This is described in more detail in Section 2.5.

- Last, but not least, is the valuable experience of flood warning staff within the Agency, particularly the Forecasting Duty Officer and those staff responsible for maintaining and developing the NFFS and its regional predecessors (Section 2.6).

2.2 Flood forecasting R&D

The EA and the Defra / EA joint floods research programme have developed a range of guidance documents for flood forecasting, including;

- rainfall measurement and forecasting,

- estuary and coastal water level forecasting, and

- fluvial forecasting.

It is not the purpose of this project to provide a detailed review of this existing work, but Table 2.1 summarises guidance available in the above areas. In addition, the OMS, which is included as an appendix to this report, should also be considered as a formal source of guidance on development of flood forecasting models.

Table 2.1: Guidelines commissioned by the Environment Agency / Defra

Document	Description	Reference
Flood forecasting and warning good practice - Baseline review (R&D Publication 131)	This review published by EA/Defra in 2002, considered the Agency's flood forecasting and warning business from a strategic viewpoint. It does not specifically give details of good practice for modelling for flood forecasting, but did identify areas of weakness in forecasting, including a need for better forecasting models for steep (fast response) catchments, and for unusual events (such as dam breaks and so on).	Defra. 2002. R&D Publication 131 (Flood forecasting and warning good practice - Baseline review)
Fluvial Flood Forecasting for Flood Warning: Real time modelling	Reviewed approaches to real time modelling, described the main issues and considerations, and provided guidance on the selection of appropriate methods for real time models for flood forecasting.	Tilford KA, Sene K, Chatterton JB & Whitlow C. 2003. R&D Technical Report W5C-013/5/TR
Fluvial Flood Forecasting for Flood Warning: Rainfall measurement and forecasting	This report comprises a detailed review of the current state of the art in rainfall measurement, a review of rainfall forecasting techniques (including numerical weather prediction models, ensemble predictions, the Nimrod and Gandolf systems) and gives details of other relevant rainfall measurement and forecasting issues.	Tilford KA, Sene K, & Collier CG. 2003. R&D Technical Report W5C-013/4/TR
Forecasting Extreme Water Levels in Estuaries for Flood Warning.	This R&D reviewed current practice for forecasting extreme water levels in estuaries. The technical report details good practice related to real time data monitoring and gives recommendations for forecasting methodologies to be used under various scenarios.	Harpin *et al*. 2002. R&D Technical Report W5/010/4
Best practice in coastal flood forecasting	Provides guidelines for appropriate selection of data sources, hydraulic process models and overall modelling solutions, focussing on detection and forecasting of coastal floods.	Defra / EA. 2003. R&D Technical Report FD2206/TR1
Benchmarking of 1-D river models	Summarises sources of numerical instability in HEC-RAS, ISIS and MIKE-11 models.	Crowder *et al*. 2004. R&D Technical Report W5-105/TR0/PR.

Of most relevance is the Real Time Modelling R&D project, led by Atkins, which reported in 2003 (Tilford *et al*., 2003). This research project reviewed and categorised the existing forecasting approaches used for fluvial flooding in England and Wales, identified the main issues and problems associated with forecasting, and produced guidelines on the selection of appropriate methods for real time models. The approaches review ranged from simple methods, such as level correlation, through to runoff models, hydrological routing and hydrodynamic routing models. This report advocates a 'horses for courses' approach (Khatibi, 2002) in which the modelling solution best suited to the nature of the forecasting problem, the catchment characteristics and project requirements is applied. The review also considered the issues associated with the use of updating and error correction methods.

2.3 Flood risk modelling guidance

The Specification for Flood Risk Mapping is used as part of the contract documentation for the Agency's Strategic Flood Risk Management Framework (SFRM). Although it is geared towards models used for mapping (sometimes referred to as "planning" or "design" models), it is also relevant to forecasting models in that it specifies good practice and certain standards for river modelling. It may be the case that the additional constraints of real-time modelling (especially the need for fast run times and numerical stability over a range of flow conditions) justify some relaxation of the specification. However, Agency project managers often use this specification, at least "loosely", as a basis for forecast model specifications.

Section 2.2 of the flood mapping specification sets out allowable tolerances for river models of ±250mm on the 100-year water level or, in tidally influenced reaches, on the 200-year water level). However this prescriptive approach is not wholly appropriate within a forecasting environment. The specification also states that the accuracy of the river model is to be such that for at least three calibration events, (covering both in and out of bank flows) the mean error plus one standard deviation of the error at all stations and over the whole time span of the events shall not exceed 150mm. It is noted, however, that these criteria are target values and a model will not be assumed to be unacceptable if it fails to meet this providing that a) the reasons for this failure are clearly stated and b) the actual accuracy is clearly stated.

Appendix D of the specification sets out further details of requirements for mathematical river models. In general any models used should be suitable to the modelled river, with a thorough review of any existing or gathered data. Hydraulic models should appropriately represent any important or relevant features that could or will influence flood hydraulics. The hydraulic model should also be accurate for a range of conditions from low flow to floodplain flow. The process of model calibration and validation should ensure that the model is adequately simulating the river system it is intended to represent.

The specification also states that not less than five calibration events and one independent event for validation should ideally be used to calibrate a hydrologic model, and three calibration events and one independent validation event should ideally be used to calibrate a hydraulic model. Model sensitivity tests are of particular importance where a full calibration/validation is not possible. The resulting model should run in a stable manner. All model files associated with the hydraulic model software used will be handed over to the Agency, along with digital and hard copies of outline and geo-referenced model schematics. It is noted, in particular, that models should be documented well enough for possible future re-use, as well as for the immediate flood risk mapping purposes; clearly this includes future use for forecasting.

The Specification for Flood Risk Mapping is prescriptive about the methods used or the reporting requirements when modelling particular features, including floodplain flows, ditches and structures. It is likely that these criteria would often need to be (and can be) relaxed for forecasting models. The specification does require a high standard of documentation within model data files and reports, which would also be recommended for forecast models, and includes:

- full river name (and reach numbers using the FDMS/NFCCD numbering system, if appropriate),
- the file name and date of last amendment and describe the condition modelled,
- the names of the modeller and the reviewer,
- identify every cross section location by watercourse, unique chainage,
- identify structures by name (e.g. road bridges),
- document all modifications from the topographical survey,
- commentary on structure coefficients (e.g. values of "k" in BERNOULLI Loss units),
- assumption behind method of modelling a particular feature,
- reference all calculations carried out in support of model parameters,
- details of boundary condition data (e.g. date of observation and zero time for observed data).

We have taken account of the criteria set out in the flood mapping specification when drafting the Protocols for forecast modelling, but with an eye to the different requirements and constraints of flood forecasting.

2.4 Software specific guidance

A range of software specific guidance is available, particularly for ISIS, HEC-RAS and MIKE 11 river modelling packages. The Agency require proforma log sheets to be completed where modelling projects use any of these software packages.

In addition the Agency recently commissioned EdenVale Modelling Services to produce a set of guidelines to assisting consultants in the preparation of flood forecasting models for use within NFFS. These 'Guidelines for Acceptance of ISIS and Other Hydrodynamic Module Datasets for Flood Forecasting' offer specific guidance on the following issues:

- initial state and conditions,

- stability and convergence properties,
- simulation parameters,
- run times and timesteps,
- chainages,
- boundary conditions,
- modelling of structures,
- limits of application, and
- changes to schematisation.

It also provides a checklist of items that should be documented.

2.5 European initiatives

2.5.1 HarmoniQuA

HarmoniQuA is an EU funded project aimed at harmonising quality assurance practices applied to catchment and river basin modelling. It is being carried out by a consortium of research institutions from throughout Europe, with the Centre for Ecology and Hydrology (Wallingford) representing the UK, and is due to be finalised in 2005.

The main deliverables of this project include a harmonised methodology with associated guidelines (generic, domain specific and integrated) for good modelling practice and a set of tools that provide the functionality to apply the method. For example, the Modelling Support Tool (MoST) provides guidance on good practices as well as facilities for recording decisions made and so on.

The HarmoniQuA approach is based on a checklist for model appraisal, with a scoring scheme used to evaluate the standard of modelling. In this system a 'deficient (score 1) / adequate (score 3) / very good (score 5)' demarcation is applied to each task, and the total project score calculated (using weights to emphasise the most critical tasks). There are many similarities between the HarmoniQuA checklist items and the supporting questions used with the Protocols.

2.5.2 Good Modelling Practice (GMP) Handbook

The Good Modelling Practice Handbook (van Waveren *et al*., 2000) was produced by a consortium of Dutch water managers and modellers as a means of promoting better modelling practice. The handbook discusses the modelling and simulation process in detail, as well as the typical pitfalls that might be encountered, and provides example checklists and flow charts for each stage. The handbook makes a significant contribution to quality assurance practice for hydrological models, and has had considerable input into the HarmoniQuA project.

2.6 FDO Handbook

The Forecasting Duty Officer's (FDO) Handbook describing the forecasting models used in the Agency's North East Region's RFFS system is a useful source of information on the issues faced in real time flood forecasting. The handbook gives details of the modelling approaches utilised within the RFFS, including problems with the application of specific models at specific sites.

3 CONSULTATION

3.1 Aims of the consultation process

The project brief included a consultation phase to seek informed views on current practice for quality checking in real-time modelling and on the desired form and use of the new protocols. A short multiple-choice questionnaire (attached as Appendix A), followed up by telephone contact, was employed as the main method of consultation.

The questionnaire asked 16 questions in total on three main themes:

1. Current practice (questions 1 to 5).

2. Use of modelling Protocols (questions 6 to 12).

3. Content of Protocols (questions 13 to 16).

Specific aims of the questions posed were to gain an insight into the following:

- the main role of the respondent within the flood forecasting business,
- the main problems encountered when developing models to be used for flood forecasting and what possible solutions might be envisaged,
- the respondent's experience of how well (if at all) current practice corresponds to the five-stage process (inception, review, calibration, testing, application) and what tasks are normally carried out at each stage,
- how Protocols might help to deliver flood forecasting models,
- how the Protocols should be applied (and why),
- what form Modelling Protocols should take to be most readily used,
- what generic topics the Protocols should cover,
- whether the Protocols should be completely generic, or whether they should focus on particular types of model,
- how much and what type of guidance should accompany the Protocols,
- who should take responsibility for enforcing the Protocols,
- who should own the Protocols and take responsibility for updating them in the future,
- the respondent's thoughts on whether the Protocols should be used as a standardised form of the summary documentation, and if so, what should be included (e.g. maps).

3.2 Respondents

The questionnaire was distributed to a number of key individuals in the Agency's flood forecasting business. It was also circulated within the National Flood Forecasting Group (NFFG) and sent to a number of consultants working within the Agency's Strategic Flood Risk Mapping Framework. Respondents are summarised in Table 3.1.

Table 3.1: Questionnaire respondents

Contact	Association
Environment Agency Staff:	
Doug Whitfield	Head Office
Shirley Greenwood	Head Office
Richard Cross	NFFWC / Midlands
Kate Scott	Southern Region (Kent)
Richard Knight	Southern Region (Kent)
Gavin Sharpin	Southern Region (Sussex)
Ian Pearce & Ben Lukey	North West Region
Rahman Khatibi	NFFG
Consultants:	
Chris Whitlow	Eden Vale Modelling Services
David Stark	Jacobs Gibb
David Worth	Posford Haskoning
Jenny Pickles	Bullen Consultants
Adrian Philpott / Kevin Sene	Atkins

Further detailed comments also came from Mike Vaughan (EA Thames), Dan Cadman (EA Head Office) and Peter Hawkes (HR Wallingford). In addition to a visit was made to the North East Region Flood Forecasting team at Rivers House, Leeds, which provided further insight on the day-to-day issues faced by forecasting teams as well as by the Forecasting Duty Officers and other end-users of forecasting models.

3.3 Summary of responses

The questionnaire responses raised a number of points.

3.3.1 Problems with current practice

The main problems in flood forecasting modelling were identified as follows:

1. It was acknowledged that there was a wide variability in skills and expertise of both Agency and consultant staff working on flood forecasting projects. This means that the Agency is sometimes unable to offer a suitable level of technical guidance to consultants, which in turn can lead to difficulty in agreeing on and attaining an appropriate type, resolution or scale of model, and a number of other technical problems. There can also be problems procuring models and agreeing a project brief for the same reasons.

2. Often there is no established knowledge base of flood forecasting issues at Area level. This has led to failure to take into account the lessons learnt from previous modelling studies. One respondent suggested that it would be helpful to have a designated person to take responsibility for all of an Area's modelling projects (whether flood risk mapping, forecasting or CFMP's). It was also felt that there was a strong need to involve end-users more directly during model inception stage, which would help to bring any specific issues to the fore as soon as possible (and avoid these being raised only during the QA process immediately before hand-over).

3. A number of inconsistencies in modelling practice were reported. These were generally thought to be inevitable due to the complexities of the approaches required, but were also linked to 'corner cutting' due to time/resources pressures. Problems prioritising the right issues were also noted – for example, one respondent highlighted that a common error is for modellers to focus on complex hydraulics at the expense of adequate consideration of real time data inputs. It was generally thought that such problems could be reduced by the use of standard modelling strategies and by measures such as Modelling Protocols.

4. Data quality and availability issues were also thought to be highly problematic. In particular problems relating to real time data and quality of real time forecasts such as rainfall and tidal surge forecasts were reported.

In general it seems that current practices are rather *ad hoc*, but broadly follow the same sequence of tasks as shown in Figure 1.1, even if they are not often considered or undertaken within such a formal five-stage framework. It is more usual for the consultant modeller to undertake Inception through to Calibration / Validation as a single 'package' and for Agency staff to undertake Testing and Application with the consultant modeller engaged only if a major model build issue is discovered. However for smaller catchments or where less complex models are applied the five stage process is rarely followed in a structured or formal manner.

The greatest inconsistencies between the idealised workflow and actual practice seem to occur during Inception and Review of the model / modelling project. It was highlighted that there was some cyclical interaction between and within these stages. For example, the division between stages is often blurred as modelling reveals the need for a change in scope or additional data collection. It was reported that, in many cases, what often starts as an exploratory model grows organically into the final model with little time available for stopping and considering whether the model could be developed differently. It was also noted that a detailed review and evaluation of existing models is often the starting point of the modelling process and should be included in the Inception stage.

One respondent thought that model selection and schematisation needs to be more closely tied into value/risk analysis, and a robust justification of the approach taken should be produced.

3.3.2 Benefits of applying Protocols

Most respondents thought that the Protocols would help to deliver better flood forecasting models. However one respondent thought that Protocols would be superfluous to existing practices advocated within the flood risk mapping modelling specification.

It was recognised that Protocols would help to ensure that a more structured, consistent modelling approach is followed, with decisions being fully documented and justifiable. In this respect Protocols are unlikely to make up for experience but will lead to at least some minimum standard being demonstrated across all Agency regions and projects.

It was also recognised that Protocols will provide a formal framework within which Agency staff might judge/evaluate the modelling procedures being applied. The Protocols will help to set out standards for procuring models by providing part of a build specification, to develop the brief, discuss actions, set milestones and to define expected deliverables.

Similarly it was thought that the Protocols would help Agency staff recognise whether quality and value were being delivered (as deviations from the expected program could be easily evaluated), which would help the project to remain focussed on its original brief, and instil a greater confidence in the final product.

3.3.3 Scope and content of Protocols

Question 13 of the consultation (Appendix 1) asked respondents “What generic topics should the Protocols cover?” and included a list of 15 choices. Most of the topics were thought appropriate for inclusion in the Protocols. However the need to balance the quantity of documentation against development effort was noted. Some respondents suggested that the Protocols should not cover catchment description, should not test the appropriateness of various modelling solutions, and should not test whether any additional functions or components should be considered for addition or removal from the model.

Some respondents did not think that the Protocols should have a role in testing the assumption and features of the modelling solution, rather that they should be used to ensure that the right steps in the modelling process have been completed with due consideration and documentation.

Respondents generally thought that the Protocols were most relevant to 1-D hydrodynamic models, hydrological routing models and rainfall runoff models (in that order). Some respondents ranked the need for Protocols for 2-D and 3-D hydrodynamic models of high importance.

It was also commented that the categories are not mutually exclusive and that the Protocols must be applicable to all of the modelling approaches within the limits of their category (i.e. it should not be expected that questions applicable to hydrodynamic models would be applicable to rule-of-thumb models).

3.3.4 Format of Protocols

In general it was thought that either a checklist or open questions would be acceptable. It was acknowledged that different combinations of checklist/question assessed by the modeller/project manager might be appropriate at different stages in the modelling process, with overall responsibility for application of the Protocols lying with the Agency project manager in close liaison with the modeller.

A couple of respondents were strongly against the use of a checklist format on the basis that "yes/no" type questions are rarely appropriate. Open questions would allow decisions to be documented without reference to documents elsewhere, and could be filled in draft by the modeller to be agreed by the Agency project manager.

Other respondents thought that a checklist was preferential so that the Protocols could be short and practical. "Implementation of Protocols is not an opportunity for debate but to ensure in plain language that the model has been challenged in a pre-agreed way and is of acceptable standard."

It was thought that the aim should be in keeping the format simple (the value being in the tests and criteria) and hence that Microsoft Word or Excel proforma would be most useful in the long-term. Preference was for an interactive Word form. However the need for flexibility was highlighted, particularly for models based on a mixture of modelling techniques or where a non-standard approach has been used. At the same time it was thought that Protocols should be a working document that should be concise, clear and efficient. Written guidance and a worked example should accompany the Protocols.

There was strong agreement that the Protocols would form a useful basis for some kind of standardised documentation. It was thought that this would help the Agency to judge proposals on a common standard, reduce the need to produce bespoke reporting, and lead to better consistency of documentation on a national level. It was also suggested that this would provide more incentive to complete the Protocols methodically.

There was a strong agreement that maps showing model nodes and flood extents etc. should be included. Some respondents also thought that it would be useful to include the other types of data in the list, however it was noted that if information is dynamic and can readily be sourced elsewhere, only a reference should be included.

3.3.5 Ownership of the Protocols

In general respondents thought that responsibility for the Protocols should lie with the Process team, NFFG, or both acting jointly. These responsibilities could include completing, archiving and updating the Protocols where appropriate.

A few respondents thought that a pre-designated person in each Region co-ordinated by the Process Team. The possibility of a pre-designated person in each Area was mentioned, allowing better application of local knowledge when ensuring that the Protocols have been met for relevant models. More generally, the possibility of an internal national quality review/acceptance group was mentioned.

One respondent thought that ‘enforcing’ was too strong a word for what are really guidelines for regional project managers and technical staff.

In general it was thought that the NFFG has a role in checking that good practice guidelines are being applied and changing the guidelines if there are good reasons, and that the same should be done with the Protocols (although some respondents thought this should be shared with the Process Team). It was suggested that when a number of shortfalls or possible improvements of the Protocols have been noted that this could then be entered onto the NFFG Agenda, giving the Process Team mandate to update them as appropriate. Some respondents also thought that the Policy Team should have a role in this.

4 MILESTONES

4.1 The need for milestones

The modelling process involves a series of key tasks and activities that need to be carried out competently and in a suitable order. Grouping these tasks into a series of stages is a logical progression, which affords the opportunity for better management of the modelling process as a whole, provides natural breaks (milestones) at which progress can be reviewed and outputs evaluated, and prevents models developing in an *ad hoc* manner.

Defining these key stages is particularly important within the context of this project, as the Protocols are to be ‘enforced’ at each stage (as shown in Figure 1.1), ensuring that the model and its key assumptions, limitations and outputs are valid, properly understood and documented, before milestones can be achieved.

4.2 Current practice

As highlighted by the consultation exercise, modelling projects are not always formally organised using milestones, with a tendency for personal preferences, project scope and model complexity to govern how the various tasks and activities are implemented. There is now much greater pressure to adopt a consistent approach at the outset, with milestones being specified within the Terms of Reference for new forecasting projects. However, in general, no one definitive set of milestones is being applied, as illustrated in Table 4.1, which compares the main milestones defined in four different modelling specifications (labelled A, B, C and D), ranging from the truly generic (A) to the catchment and end-use specific (D).

The specifications detailed in Table 4.1 include that applied within the HarmoniQuA Modelling Support Tool (MoST). This is a ‘classical’ approach to modelling, which is applicable to all types of catchment and river basin models (i.e. including but not restricted to forecasting applications) and is very generic in nature. At the other end of the scale is the modelling specification for the River Ribble Flood Forecasting Improvements Project (EA, North West Region) in which existing hydrodynamic models for the River Ribble are to be developed for real time application. In contrast this specification makes assumptions about the model structure and data at the outset, with a greater focus on practical issues, such as documentation and model handover.

The stages defined in two previous draft versions of the Outline Modelling Specification (OMS) are also included. These are actually fairly different, which highlights the variation in priorities that exist within the Agency itself. The stages defined in the AFFMS Specification (Cadman, 2002) are similar those applied in HarmoniQuA, although the steps are broken down into more detail. In the GMS Draft B (Khatibi, 2002) the bulk of the model conceptualisation and build is included in the inception stage. This is perhaps misleading to modellers and does not reflect current practice, in which most effort is likely to be focussed on model build. However, it does include a vital stage in the modelling process, that of review to ensure that the model is parsimonious and robust, which is omitted in the other specifications.

Table 4.1: Comparison of key 'milestones' in four modelling specifications

Mile-stone	A HarmoniQuA	B AFFMS Spec.	C GMS DraftB	D River Ribble
1	Purpose & conditions (model study plan)	a) Outline catchment conceptualisation & b) Outline modelling proposal	Inception	Project inception
2	Data & conceptualisation	a) Detailed catchment conceptualisation & b) Detailed modelling proposal	Review	Model build
3	Model set-up	Modelling database	Validation	Calibration and performance analysis
4	Calibration / validation	Configuration, calibration and validation	Test Controlling	Project outputs
5	Prediction	Forecast model build and calibration	Application	Model handover

Sources:
A - Steps defined in HarmoniQuA and applied in the Modelling Support Tool (MoST).
B - The generic specification for lumped conceptual hydrology/hydraulic models (Cadman, 2002) as stated in the Anglian Flow Forecasting Modelling System (AFFMS).
C - Draft B version of the NFFS's Generic Modelling Specification for flood forecasting (Khatibi, 2002).
D - The modelling specification for the River Ribble Flood Forecasting Improvements Project (EA, NW).

4.3 Proposed approach

Given the inconsistencies highlighted in both the review of current practice (Section 4.2) and consultation (3.3) it seems clear that the milestones presently advocated ('C' in Table 4.1) need to be revised. However, to keep in line with the current strategy, it seems useful to retain the five-stage division of the modelling process. The key stages being proposed are therefore as follows:

Stage 1. Inception,

Stage 2. Conceptualisation and configuration/build,

Stage 3. Review,

Stage 4. Calibration and validation,

Stage 5. Testing.

The detail of each stage is summarised in Table 4.2. The main change is the inclusion of a single stage representing detailed conceptualisation and model build. This is in recognition of the effort that is typically required to reconcile different data sources and to build a model solution – this can be particularly time consuming where a complex modelling approach is required. It also covers both development of a new model from scratch and modification or re-use of existing models for flood forecasting. This is a distinct stage, separate from Inception, because it involves actual modelling work using software and data sets, which, it is suggested, is not part of an Inception stage.

Table 4.2: Proposed milestones to be applied in modelling practice for flood forecasting models

Stage or Milestone	Tasks	Details and aims	Output
1: Inception	- Identify available data - Review of existing models -Catchment characterisation - Schematisation	The model inception phase. Scoping of potential modelling approaches based upon forecasting requirements, data availability, previous studies and key aspects of the physical system. Leading to specification of modelling approach and preliminary model schematisation.	- Inception report - Technical programme - Preliminary schematisation - Model risk register
2: Conceptualisa-tion and configuration	- Collation & quality assurance of data - Manipulation / process of data - Quantification of catchment processes - Detailed model schematisation - Initial model build	Detailed conceptualisation of the hydrologic and hydraulic behaviour of the physical system, discretisation into channel reaches or subcatchments as appropriate. Detailed schematisation of the model. Verification of input data and subsequent manipulation to evaluate model parameters. Progression to model build using proprietary software package or bespoke programming.	- Project data register - Model build log - 'Raw' model
3: Review	- Review of raw model - Sensitivity tests	Review to ensure model is parsimonious and that all model components are necessary, using sensitivity tests if appropriate. Revision of built model if required.	- Interim report - 'Parsimonious' model
4: Calibration and validation	- Calibration - Validation	Calibration and validation phases, where model parameters are optimised by referencing the model outputs to observed data. Test of numerical robustness, and sensibility of outputs.	- Calibration report - 'Validated' model
5: Testing	- Offline testing - Testing in emulated real time	The test controlling phase where the model is tested both offline, and within an emulated real time environment.	- Full modelling report - 'Tested' model

The Review stage has been retained, as the need to ensure that the model runs efficiently is especially important where the model is required in real time, and is often overlooked when constructing design models. Application of the tested model on an operational basis is no longer included as it is unlikely to require significant input from 'the modeller', and is therefore beyond the scope of both the Protocols and the GMS.

It is important to stress that feedback will be an important element between the different stages of the modelling process. For instance the Review process may suggest that the model is too complex, leading the modeller back to stage two. Similarly, if a satisfactory calibration could not be achieved, the modeller may wish to revise how the catchment has been conceptualised. In many cases there will be a continual cycling between stages until satisfactory result/output has been achieved

Furthermore it should not be assumed that the Client (i.e. the Agency project manager and team) would only have input at the inception stage of the project. A two-way flow of information between the project manager and modeller is envisaged at all stages in the modelling process. In fact application of the Protocols will help to ensure that Agency staff are aware of progress and "performance" of the model at the end of each stage.

5 PROTOCOLS

5.1 Structure of the Protocols

The structure and format of the Protocols, and the manner in which they are applied, is perhaps as important as the Protocols themselves. As discussed in Chapter 3, many of the questionnaire respondents had strong feelings regarding this issue, but there was not a consensus view, with some individuals favouring a checklist format where specified activities must be 'ticked off' and others fervently advocating a less prescriptive approach with open questions to which more qualitative responses could be given.

A possible third option considered was to apply a scoring system similar to that used the HarmoniQuA project, in which a 'deficient (score 1) / adequate (score 3) / very good (score 5)' demarcation is applied to each task. The total project score is then calculated using weights to emphasise the most critical tasks, although a simpler system would be to ensure that at least 'adequate' is achieved for all questions before the project, as a whole can be approved. This approach was not adopted because the main intention of the Protocols is to ensure that important issues and decisions have been considered, justified and documented. The Protocols were not intended to score projects for quality, but rather to help 'catch' exceptions.

The approach taken is an attempt to reconcile the rather contrary points of view expressed by consultation respondents. Here the Protocols are, for each milestone, a series of statements that define the minimum level of consideration and documentation required. To provide guidance for modellers and Agency project managers (especially those with less experience of real-time model development), sets of supporting questions are defined for each Protocol, these being more specific in nature. Table 5.1 gives an example of the structure adopted.

Table 5.1: Structure of the Protocols for creating minimum standards in modelling

Protocol 2.1 – Statement describing the first Protocol applicable to Milestone No. 2
Q2.1.1 First supporting questioning to Protocol 2.1? *Q2.1.2 Second supporting question to Protocol 2.1?* *Q2.1.3 Third supporting question to Protocol 2.1?*

5.1.1 Protocol statements

In an effort to be succinct, and bearing in mind that each Protocol may require a number of supporting questions, the number of protocols defined for each milestone has been kept to a minimum. In total 27 protocols, listed in Table 5.2, are proposed. Of these, six are relevant to the Inception stage, five protocols cover Conceptualisation/Configuration stage, three protocols apply to Review, seven protocols apply to Calibration/Validation and five protocols cover the Testing Stages. As discussed previously, none of the protocols explicitly test the model solution being applied. However, if the modelling approach is unsuitable, this should become evident when applying the Protocols for Milestones 2 and 3.

Table 5.2: Protocols for minimum standards in modelling

Mile-stones	Protocol	Statement
1. Inception	1.1	The flood forecasting requirements are fully understood and agreed by both client and modeller
	1.2	Consideration has been given to previous work / models and their implications
	1.3	Consideration has been given to which particular catchment features are significant
	1.4	The proposed modelling approach is justified
	1.5	Consideration has been given to data requirements and availability
	1.6	A fully documented preliminary model schematisation has been submitted, including a schematic of the main elements
2. Conceptual-isation & configuration	2.1	Appropriate software tools have been selected for model build
	2.2	Quality assurance procedures have been applied to input data
	2.3	The raw model meets the requirements of the brief
	2.4	The raw model meets a minimum quality standard
	2.5	The resolution of the model is acceptable
3. Review	3.1	Model is parsimonious
	3.2	Model is robust when simplified
	3.3	The model appears to run fast enough for real time use
4. Calibration & validation	4.1	Calibration criteria are clear
	4.2	Calibration and validation data are representative of operational conditions
	4.3	Performance of calibrated model is acceptable
	4.4	Model parameters are plausible and acceptable
	4.5	Model performs well with validation data
	4.6	Limitations of validated model are understood and acceptable
	4.7	Calibration and validation procedures are well documented
5. Testing	5.1	A plan for testing the model has been specified and agreed
	5.2	Model runs correctly in emulated real time forecasting network
	5.3	Model performance is stable in emulated real time use
	5.4	The model runs fast enough to achieve the required lead time
	5.5	An updating or error predicting scheme is used if applicable
	5.6	Operating uncertainties and issues are documented

The Protocols have been kept deliberately generic, in order to be applicable to all possible modelling approaches. It is then up to the modeller and/or project manager to interpret the scope of the Protocol for a given approach. A number of protocols therefore take the form "consideration has been given", because the important thing is to check that the modeller has taken notice of certain factors, without necessarily assuming that there should be a particular response (e.g. 1.2, 1.3). For the same reason the Protocols do not attempt to test the assumptions or configuration of the modelling solution, but rather to ascertain that the modeller has done so.

5.1.2 Supporting questions

The supporting questions provide a more structured means for the modeller and Agency project manager to assess whether minimum standards have been achieved for each Protocol. They are focussed questions that can generally be answered with a yes/no response, and therefore form the checklist element of the Protocols.

The list of questions can be viewed as a task list, and provides informal guidance to modellers and managers as to what kinds of activities should be carried out within each stage of the modelling, and in this respect will tie in closely with the formalised guidance provided by the Outline Modelling Specification (Appendix 3).

The supporting questions are not necessarily exclusive, that is, for particular projects the project manager may wish to add additional checklist items in line with the project brief. However the supporting questions are more approach-focussed than the Protocols, and some are relevant only to particular methods.

5.2 Protocols and supporting questions in detail

5.2.1 Stage 1: Inception

<u>Protocol 1.1 - The flood forecasting requirements are fully understood and agreed by both client and modeller.</u>
The role of this Protocol is to ensure that the client and modeller are fully agreed, at the outset of the project, as to the requirements of the modelling, such as the operating platform, degree of complexity, performance targets and so on. However, the intention is not to question whether these requirements are appropriate. Six supporting questions are used to assess whether the Protocol has been achieved, as follows:

Q1.1.1 Are both parties clear regarding the operating platform / environment in which the model is to be run?

Q1.1.2 Are both parties agreed on the level of sophistication of model required?

Q1.1.3 Have the forecast points, lead times and other performance criteria been agreed?

Q1.1.4 Have target values for model resolution / accuracy been agreed, and what are the allowable tolerances?

Q1.1.5 Has the use of real time updating/ error correction procedures been agreed?

Q1.1.6 Are both parties agreed about the data sources to be used for real time modelling?

Protocol 1.2 - Consideration has been given to previous work/models and their implications

Ensuring that previous models (and lessons learnt from them) are considered was something that emerged from consultation as a strong concern, particularly where existing flood warning systems or flood risk mapping models for the area of interest are to upgraded or adapted. The Protocol is therefore used to ensure that previous models are fully reviewed. Four supporting questions apply:

Q1.2.1 Have existing hydrologic/hydraulic models relevant to the study area been identified?

Q1.2.2 Have the quality of existing models and the data on which they are based been examined, documented and any potential problems highlighted?

Q1.2.3 Have any weaknesses of existing models and/or modelling approaches been identified and documented?

Q1.2.4 If parts of existing models are being reused, have they been thoroughly checked (e.g. are cross section data up to date)?

Supporting question 1.2.4 is particularly important because existing models may no longer reflect what happens on the ground (e.g. due to physical change of the river system, the internal interpolation using in models) or the methods (& software) used might have been superseded or improved.

Protocol 1.3 - Consideration has been given to which particular catchment features are significant.

The need for this Protocol is really self-evident. However it should be noted that it is not expected that the catchment processes will be characterised in detail at the inception stage.

Each of the following features should be considered and evaluated:

Q1.3.1 Backwater effects

Q1.3.2 Floodplain storage / conveyance

Q1.3 3 Confluences

Q1.3.4 Tidal influences

Q1.3.5 Typical speed of response in the catchment

Q1.3.6 Typical bed slope

Q1.3.7 Snowmelt

Q1.3.8 Groundwater and surface water interactions

Q1.3.9 Abstractions and discharges

Q1.3.10 Intakes and flood relief channels

Q1.3.11 Reservoirs and lakes

Q1.3.12 Sluices, gates – operational rules

Q1.3.13 Bridges and culverts causing significant constriction or afflux

Q1.3.14 Urbanisation

<u>Protocol 1.4 - The proposed modelling approach is justified</u>
The proposed modelling approach will typically have been decided in accordance with Good Practice guidelines prior to the modelling. This Protocol is more of a 'double-check' to ascertain that any weaknesses of taking this approach are understood by the modeller, that these can be reconciled against the requirements of the study, and that suitable methods for implementing the approach are available to the modeller. Supporting questions are therefore as follows:

Q1.4.1 Is the proposed modelling approach broadly applicable, given the flood forecasting requirements?

Q1.4.2 Is the proposed approach suitable given the hydrologic and hydraulic characteristics of the river / catchment?

Q1.4.3 If a hybrid approach is used, has thought been given to the consistency of the different elements?

Q1.4.4 Can the data requirements of the proposed modelling approach be met?

Q1.4.5 Are appropriate tools available to build and calibrate the proposed type of model?

Q1.4.6 Are the assumptions and uncertainties of the approach recognised and documented?

<u>Protocol 1.5 - Consideration has been given to data requirements and availability</u>
The role of this Protocol is to ensure that data requirements and availability are considered at an early stage in the project. Detailed investigation of data sources, such as checking reliability, is not relevant at this stage and is addressed in later Protocols. There are three supporting questions, of which 1.5.3 is particularly essential for forecasting modelling.

Q1.5.1 Have key data requirements (to cover hydrologic, hydraulic and geographical parameters) been identified?

Q1.5.2 Have the required data been sourced? (by consultation with relevant Agency staff and/or external organisations and agencies where necessary).

Q1.5.3 Have all available telemetry inputs been identified?

Protocol 1.6 - A fully documented preliminary model schematisation has been submitted, including a schematic of the main elements

This Protocol ensures that a detailed plan of the proposed model has been submitted to the Agency, and accepted, which is a vital prerequisite to any model build.

Q1.6.1 Has a preliminary model schematic been produced and accepted by the client?

5.2.2 Stage 2: Conceptualisation & configuration

Protocol 2.1 - Appropriate software tools have been selected for model build

This Protocol is included in an attempt to head off any future problems owing to software compatibility.

2.1.1 Is the software package (and version) to be used appropriate given the model requirements?

2.1.2 Is the software package (and version) compatible with NFFS and approved for use?

2.1.3 Is the modeller aware of the weaknesses and drawbacks of the software?

2.1.4 If a bespoke model is required, is this cost effective and justifiable?

Supporting question 2.1.4 (bespoke programming) is to ensure that any non standard software being used/required to implement the modelling approach is justifiable and that is also compatible with NFFS.

Protocol 2.2. Quality assurance procedures have been applied to input data

At this stage, where the model elements are being assembled, it is important to ascertain that data sources are reliable. This Protocol therefore addresses quality assurance of input data, with three supporting questions used to assess whether this is achieved:

2.2.1 Have obtained data been documented in a project data register?

2.2.2 Has an audit of the quality/reliability of each input data set been carried out and documented?

2.2.3 Are methods used to manipulate data (if required) appropriate and acceptable?

Protocol 2.3 – The raw model meets the requirement of the brief

This Protocol is to check that the computation, as implemented, does meet the requirements already identified (in Protocol 1.3). The detail very much depends on the complexity of the catchment, and so the supporting question has been posed in rather generic terms as follows:

2.3.1 Does the model reflect the key features of the system, as identified in Protocol 1.3?

Protocol 2.4 - The raw model meets a minimum quality standard

Stage 2 is intended to deliver a 'raw' model that is either a new build or adaptation. The supporting questions for this Protocol cover some very basic checks aimed at ensuring that the modelling is being built to good standards.

Q2.4.1 If the model has been discretised into separate subcatchments / reaches, have these been joined adequately?

Q2.4.2 Is the model extent reasonable (i.e. how does the length of the modelled reach compare to the real river length)?

Q2.4.3 Are the method(s) of defining model boundaries appropriate and have they been adequately documented?

Q2.4.4 Are the method(s) used to define fixed/geometric model parameters appropriate and have they been adequately documented?

Q2.4.5 Are rules for gate and barrage operation adequately documented and checked?

Q2.4.6 Has the modeller followed model/software specific guidelines where available (e.g. Guidelines for Acceptance of ISIS and Other Hydrodynamic Module Datasets for Flood Forecasting).

Protocol 2.5 - The resolution of the model is acceptable

As with Protocol 2.4 these supporting questions are aimed at ensuring that the modelling is being built to good standards, in this case focussing on temporal and spatial resolution of the model

Q2.5.1 Is there justification of the selected time step (is it small enough)?

Q2.5.2 Is the spatial resolution sufficient to represent key controls?

5.2.3 Stage 3: Review

Protocol 3.1 - Model is parsimonious

This Protocol, applied at the review stage, is used to make sure that the model is no more complicated that can be supported by the available data. Five supporting questions are used as follows:

Q3.1.1 Are time and spatial resolutions no more detailed than strictly necessary?

Q3.1.2 Has a check been made for structures, junctions and controls that do not affect the forecast and can be removed from the model?

Q3.1.3 Has a check been made for any hydrodynamic reaches that can be simplified to routing reaches?

Q3.1.4 Has a check been made for any sub-catchments or reaches that can be combined?

Q3.1.5.Has a check been made for 'surplus' cross sections?

Protocol 3.2 - Model is robust when simplified

The role of this Protocol is to ensure that any simplifications do not lead to an unacceptable loss of accuracy or stability. The supporting questions are as follows:

Q3.2.1 Does decreasing the cross-section spacing reduce stability / accuracy?

Q3.2.3 Does the representation of floodplain storage affect the model stability or accuracy?

Q3.2.3 Does simplification of structures lead to a loss of stability or accuracy?

Protocol 3.3 - The model appears to run fast enough for real time use.

By the end of the review stage a parsimonious model should be developed. An important consideration is that the model run time should be appropriate for real time use.

Q3.3.1 Has the run time of the model been checked in relation to the required lead time?

5.2.4 Stage 4: Calibration and validation

Protocol 4.1 - Calibration criteria are clear

The aim of this Protocol is to ensure that there is an agreed and documented basis for calibration. Because of the variety of model types, the three supporting questions are not prescriptive about the methods used (for calibration).

Q4.1.1 Have locations used for calibration (e.g. forecast points / downstream boundary gauged data) been documented and agreed with the client?

Q4.1.2 Have the criteria for calibration been documented and agreed (e.g. R^2*, visual fit, RMSE)?*

Q4.1.3 What 'sensibility tests' are to be applied (e.g. channel capacity is sensible relative to median annual maximum flood)?

Protocol 4.2 - Calibration and validation data are representative of operational conditions

This Protocol is to check that the calibration and validation model is applicable to conditions likely to be encountered during operation of the forecasting system and not merely a 'special case'. Seven supporting questions are required as follows:

Q4.2.1 Have you checked that the calibration data are of the same type and resolution as real-time data?

Q4.2.2 Is the calibration data of sufficient resolution to be able to resolve the features of the hydrograph that are of most relevance?

Q4.2.3 Are the flow conditions represented in the calibration data of sufficient range, given the scope of the model (including the effects of any artificial influences)?

Q4.2.4 Does the calibration data include at least one significant flood event (where flows are larger than QMED or out of bank)?

Q4.2.5 Has the quality of event data used in calibration been reviewed and accepted?

Q4.2.6 Where there are periods of missing data within calibration events, have appropriate decisions been taken and documented as to whether these should be infilled or whether the event should be rejected from the calibration?

Q4.2.7 Are calibration events representative of current catchment conditions? (Have there been any recent works or events in the catchment that may have modified the hydrologic / hydraulic regime)?

<u>Protocol 4.3 - Performance of calibrated model is acceptable</u>

This Protocol considers model performance in broad terms rather than concentrating on one numerical measure. In particular, the need for checks with local staff was an issue highlighted during consultation. The following supporting questions apply:

Q4.3.1 Does the model fit the hydrograph peaks (magnitude and timing) and rising limb according to the agreed criteria?

Q4.3.2 Does the model also simulate the full flow range to an agreed standard of performance?

Q4.3.3 Do the model outputs look reasonable at flows higher than the calibration event data?

Q4.3.4 Are flood storage areas modelled adequately during a large or multi-peak event?

Q4.3.5 Are there any unexplained head losses (e.g. at structures) in the model results?

Q4.3.6 Have the outputs been reviewed by Area or Regional staff with local knowledge?

<u>Protocol 4.4 - Model parameters are plausible and acceptable</u>

Here the term 'plausible' means that values appear realistic (e.g. are of the expected order of magnitude, or within an acceptable range). It is recognised that model parameters may sometimes compensate for errors in model structure /data yet still provide realistic predictive performance. The supporting questions are divided according to model type.

Q4.4.1 Has the sensitivity of the model output to parameter values been evaluated?

<u>*Transfer function models*</u>

Q4.4.2 Are the time delay and gain parameters plausible?

<u>*Rainfall-runoff models*</u>

4.4.3 Are the values of store depths and time constants physically realistic?

Kinematic Wave models

4.4.4 Are wave speed and attenuation parameters realistic?

Hydrodynamic models

4.4.5 Are channel roughness values realistic?

4.4.6 Does model attenuation match with actual?

4.4.7 Are weir coefficients and bridge losses physically realistic?

4.4.8 Are spill coefficients applied at washlands and overland flow paths realistic?

Protocol 4.5 - Model performs well with validation data

The supporting questions for calibration may also be useful when assessing this Protocol, but have not been specified separately here for flexibility and to avoid repetition.

4.5.1 Does the model perform to agreed and documented criteria for the validation event(s)?

Protocol 4.6 - Limitations of validated model are understood and acceptable

This Protocol is aimed at ensuring that there is some understanding of the possible shortcomings of the model if it is used beyond the range of conditions tested.

4.6.1 Does the model perform sensibly when extrapolated to more extreme conditions?

4.6.2 Has the Agency project manager been advised of the limitations of the validated model?

Protocol 4.7 - Calibration and validation procedures are well documented

This Protocol addresses the need for adequate documentation – this should be sufficient to allow the results of calibration and validation procedures to be recreated. Depending on the project brief this may include a model risk register.

4.7.1 Has a project report or record been delivered?

4.7.2 Have document, model and data files been delivered?

5.2.5 Stage 5: Test controlling

Protocol 5.1 - A plan for testing the model has been specified and agreed

The test controlling stage is crucial to ensuring that the model is able perform adequately in an operational environment. This Protocol therefore addresses the need to ensure that there is close liaison between the modeller and client with regard to which specific tests are required.

Q5.1.1 Has a set of test runs been agreed & documented?

Protocol 5.2 - Model runs correctly in emulated real time forecasting network

This Protocol is used to assess the ability of the model to make accurate predictions in the test controlling environment. However, it is a check that the software is working rather than the model being suitable for real time use (which is covered in following Protocols). The relevant supporting checklist items are as follows:

Q5.2.1 Will the model run for calibration events in the test-control environment?

Q5.2.2 Are the results in the test–control environment the same as for off-line calibration or validation?

Q5.2.3 Has the link between the model and other components of the network been checked?

Q5.2.4 Can differences between model runs using actual and forecast data be explained?

Protocol 5.3 - Model performance is stable in emulated real time use.

Consultation suggested that this stage is not always carried out, but it should be an important part of test controlling. The following supporting questions are used to assess model performance in emulated real time:

Q5.3.1 Is the model robust to reasonably foreseeable drop-outs or errors in the input data (e.g. forecast rainfall, telemetry)?

Q5.3.2 Do time-varying parameters change smoothly?

Q5.3.3 Is the model stable for both cold and hot starts (i.e. for varying run-in times)?

Q5.3.4 Will the model run over a sufficiently wide range of flow conditions for real-time use?

Q5.3.5 Is the river model stable for reasonably foreseeable start-up conditions?

Q5.3.6 Is the river model stable for reasonably foreseeable downstream boundary conditions?

Q5.3.7 Are the lowest stable flows documented?

Protocol 5.4 - The model runs fast enough to achieve the required lead time.

Model run speed is a very important consideration for real time use, this Protocol is applied to make sure that the delivered model is capable of providing the necessary lead time for a range of start up conditions.

Q5.4.1 Can the model provide the required lead time over a range of initial and input conditions?

Protocol 5.5 An updating or error prediction scheme is used if applicable

This Protocol is only applicable if updating or error prediction, and appropriate telemetry data are available. Four supporting questions are used to assess what if the use of updating or error prediction schemes, without being prescriptive about the methods used.

Q5.5.1 Is state-updating used?

Q5.5.2 Is error prediction used?

Q5.5.3 Are updating or error prediction stable over a range of different events?

Q5.5.4 If there is significant variation between consecutive forecast runs can this be explained by the error correction or updating procedures?

<u>Protocol 5.6 Operating uncertainties are documented.</u>
This Protocol is to ensure that operating uncertainties are summarised and recorded. Such information should be readily available to Agency staff who will use the model operationally and is also a vital for determining performance measures (of the model predictions). The supporting questions used here are as follows:

Q5.6.1 Has the change in uncertainty with increasing lead time been checked?

Q5.6.2 Are there features of the catchment that may introduce uncertainty because they cannot be modelled, such as control structures not operating to prescribed rules or reservoir spills?

Q5.6.3 Have the operating uncertainties been documented in the project report?

5.3 Applying and enforcing the Protocols

The question of if and how the Protocols should be enforced raised a number of strong responses during the consultation. This discussion mainly relates to whether the Protocols should be considered as a form of 'guidance' or viewed as 'stipulations'. There was a general feeling that the Protocols should not restrict experienced modellers from 'getting on with the job' and some of the consultees suggested that the Protocols should not be 'enforced' at all. However, it is clear that a general level of compliance with the Protocols needs to be demonstrated in some way if we are to be confident that minimum standards have been achieved.

As discussed in Section 5.1, each Protocol is to be assessed by answering its set of supporting questions. However these questions are, by nature of the project brief, relatively generic. It is recognised that not all models/modelling projects will follow such an idealised format and there may be cases where particular issues not covered by the supporting questions become important, yet others where certain supporting questions become redundant.

The questions are not therefore intended as a formalised checklist, nor are they intended to be exclusive. Rather the answers to the supporting questions are intended to help the project manager and/or modeller to determine whether the modelling procedure generally complies with the Protocol statement. That is, not all the supporting questions would necessarily have to be "passed" for the Modelling Protocol to be met or, conversely, it would be possible for all the supporting questions to be answered satisfactorily, but for the modeller or project manager to feel that the modelling procedure does not meet the Protocol.

The key issue is that all supporting questions should be answered as fully as possible. In order to achieve this, it is recommended that a proforma document be used. This would provide a structured and consistent way of recording any decisions regarding compliance with Protocols and documenting the most critical and fundamental aspects of the modelling. A proforma document has been produced to accompany this project, and this is likely to be made available via the Agency's intranet.

The Protocols for each milestone or stage in the modelling process are to be assessed retrospectively when the stage is completed. Thus, if there is a case for 'failing' any of these Protocols, there is a need, and an opportunity, to readdress them before moving on to the next stage. The flow chart shown in Figure 5.1 illustrates how the process of applying the Protocols fits into the overall modelling cycle. It is useful to highlight again, that Protocols are used to assess that tasks have been carried out to a minimum standard - therefore compliance of all Protocols associated with any particular stage simply means that the modeller has carried out or considered relevant tasks and activities. Compliance with Protocols indicates that a minimum standard has been applied to the task, but the Protocols do not in themselves test the modelling output – for instance compliance with Protocols in Stage 4 (Calibration) does not necessarily mean that optimum forecasting performance can be achieved if data inputs are unreliable; in this case the modeller may have to loop back to an earlier stage of the process to seek improvements (as illustrated by the red lines Figure 5.1).

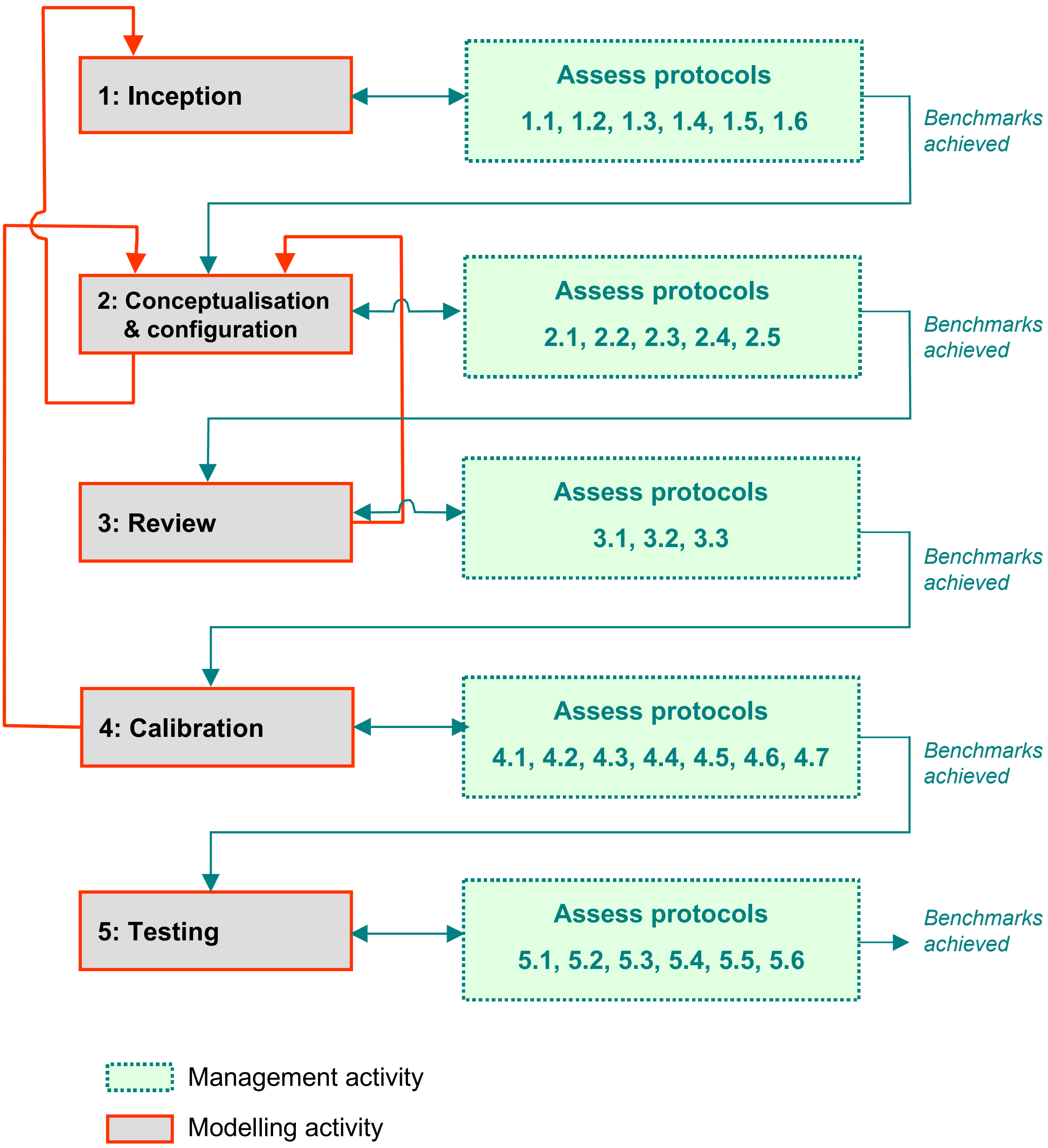

Figure 5.1: Assessing compliance at modelling milestones

6 CASE STUDY EXAMPLE 1

6.1 Background

This chapter reports the first of the two example applications of the modelling Protocols. It should be noted that the Protocols have been applied after completion of the projects, and therefore neither of the case studies represents a trial run of the Protocols.

This example uses a modelling project commissioned by North East Region of the Environment Agency and carried out by JBA Consulting. The objective of the project was to produce an unsteady model of the Yorkshire Ouse. The model was based on existing hydrodynamic or routing models, prepared by other consultants at various times. The extent of the final model is shown in Figure 6.1.

Figure 6.1: River Ouse (Yorkshire) case study – model extents.

The model was commissioned as part of a project to replace the River Flow Forecasting System (RFFS) with the new National Flood Forecasting System (NFFS). It will provide real-time river level forecasts for a series of locations on the River Ouse and River Wharfe.

6.1.1 Study brief

The Agency's key requirements for the unsteady model were as follows:

- Model should be built using ISIS software.

- Mathematical stability throughout the full range of flow and tidal conditions.

- Model run times of less than 5-minutes for a simulation of a 48-hour forecast period on a machine with equivalent processing speed to the Compaq ProLiant DL580.

The study did not include a requirement for testing within an emulated real-time environment; this was to be done by the Environment Agency following delivery of the model and roll out of NFFS. However, the two key requirements set out above represent a clear understanding on the part of the client and the consultant that the delivered model should be suitable for real-time use. This understanding was explicit throughout the project and informed many of the decisions made during model development.

6.2 Application of Protocols for minimum standards

The project was not to develop a new forecasting model from scratch. As is often the case, there were several existing models within the study extents. The existing models had not been developed for flood forecasting. The brief was to make use of these models and adapt them for forecasting use where necessary.

The project did not follow the programme of milestones as set out in this report. However, in applying the Protocols it is not difficult to fit the actual work done into the stages and milestones proposed here. It is noted again that the staged approach is presented as something of an idealisation of actual practice, and that projects may sometimes combine or split stages according to circumstances. In setting this project out as a case study, we have interpreted the work done as if it had followed the idealised stages.

In this case, the Inception and Configuration milestones concentrated on collating, reviewing, combining and extending existing models and data sets. The ‘raw model’ (although not named as such in the original project) was therefore more complex and detailed than needed and also too slow to run. The Review milestone was therefore of particular importance. In this case, Review and Calibration and Validation were effectively combined in a process of model simplification.

The final milestone stage, Testing, is included here because some of the work carried out within the original project is relevant, even though the consultant was not required to test the model in emulated real-time.

The following tables, (Table 6.1 to Table 6.5) illustrate the completion of each Protocol. Answers to the supporting questions are given along with more open-ended comments. Compliance with the Protocols has been assessed by ensuring that the majority of supporting questions can be answered affirmatively, unless they are not applicable (N/A).

Table 6.1: River Ouse case study – Milestone 1

MILESTONE 1. INCEPTION

1.1 The flood forecasting requirements are fully understood and agreed by both client and modeller

Q1.1.1 Are both parties clear regarding the operating platform / environment in which the model is to be run?

- *Yes, stand-alone model suitable for eventual use within NFFS.*

Q1.1.2 Are both parties agreed on the level of sophistication of model required?

- *Yes, extension (in space) and simplification of existing hydrodynamic models.*

Q1.1.3 Have the forecast points and lead times required, and other performance criteria been agreed?

- *Forecast locations specified but lead time N/A (requirement is to run a 48-hour forecast).*

Q1.1.4 Have target values for model resolution / accuracy been agreed, and what are the allowable tolerances?

- *No specific target values set. Section 105 Specification (Appendix D refers – specifies general standards for model build and targets for variation in channel conveyance between sections).*

Q1.1.5 Has the use of real time updating/ error correction procedures been agreed?

- *Not required, as the client will do the work to implement the model within the forecasting system.*

Q1.1.6 Are both parties agreed about the data sources to be used for real time modelling?

- *Yes, detailed review of hydrometric data included in project.*

Comment:
The main requirements of the project in this case are for delivery of a hydraulic model. Implementation in a real-time forecasting environment is to be undertaken by the client, not the consultant.

1.2 Consideration has been given to previous work / models and their implications

Q1.2.1 Have existing hydrologic/hydraulic models relevant to the study area been identified?

- *Existing ISIS models: one for the River Ouse (Skelton to the River Derwent confluence) from Bullen Consultants Ltd. and the other for the upper River Aire (upstream of Chapel Haddlesay) from WS Atkins. An existing MIKE11 model of the lower Ouse (tidal limit to the River Trent confluence) from ABP Marine Environment Research Ltd.*

Q1.2.2 Have the quality of existing models and the data on which they are based been examined, documented and any potential problems highlighted?

- *Yes, final report Section 2 details sources of data in the original models.*

Q1.2.3 Have any weaknesses of existing models and/or modelling approaches been identified and documented?

- *Models were checked, including particularly the rating curves for gauging stations.*

Q1.2.4 If parts of existing models are being reused, have they been thoroughly checked (e.g. cross section data is up to date)?

- *Yes.*

Comment:
The project brief was to combine, extend and simplify existing models hence this has been a critical aspect of the study.

1.3 Consideration has been given to which particular catchment features are significant

Q1.3.1 Backwater effects

- *Yes, hydrodynamic model.*

Q1.3.2 Floodplain storage

- *Yes, to be represented by RESERVIOR units in revised ISIS model.*

Q1.3 3 Confluences

- *Yes, represented explicitly.*

Q1.3.4 Tidal influences

- *Yes, Barmby barrage represented.*

Q1.3.5 Typical speed of response in the catchment

- *Yes, lag analysis carried out.*

Q1.3.6 Typical bed slope

- *Accounted for in HD model.*

Table 6.1: River Ouse case study – Milestone 1

Q1.3.7 Snowmelt

- *N/A as not a rainfall-runoff model.*

Q1.3.8 Groundwater and surface water interactions

- *N/A*

Q1.3.9 Abstractions and discharges

- *None significant for flood forecasting.*

Q1.3.10 Intakes and flood relief channels

- *None significant for flood forecasting (though Foss Barrier considered but not included).*

Q1.3.11 Reservoirs and lakes

- *N/A*

Q1.3.12 Sluices, gates – operational rules

- *Yes, tidal barrage.*

Q1.3.13 Bridges and culverts causing significant constriction or afflux

- *Considered to be well represented in original models.*

Q1.3.14 Urbanisation

- *N/A as not a rainfall-runoff model.*

Comment:
The project brief is to deliver a river model that will accept inputs from either gauging station data or separate rainfall-runoff modelling. The Protocols are designed to be applied to each separate model within a forecasting network, hence there is no need here to consider factors such as urbanization and snowmelt, although these would be relevant for any rainfall-runoff models that might be used to generate forecast inputs to the river model.

1.4 The proposed modelling approach is justified

Q1.4.1 Is the proposed modelling approach broadly applicable, given the flood forecasting requirements?

- *Yes, HD modelling*

Q1.4.2 Is the proposed approach suitable given the hydrologic and hydraulic characteristics of the river / catchment?

- *Yes, tidal boundary and floodplains mean HD model is justifiable.*

Q1.4.3 If a hybrid approach is used, has thought been given to the consistency of the different elements?

- *N/A*

Q1.4.4 Can the data requirements of the proposed modelling approach be met?

- *Yes, existing models and hydrometric data are available from the Environment Agency.*

Q1.4.5 Are appropriate tools available to build and calibrate the proposed type of model?

- *Yes, ISIS v2.1*

Q1.4.6 Are the assumptions and uncertainties of the approach recognised and documented?

- *Yes, requirement for accurate survey data, representation of structures and hydrometric data.*

Comment:
The river Ouse and tributaries are a complex system that includes floodplain storage, confluences, a tidal boundary condition and many structures. These factors tend to favour use of a hydrodynamic model. Although it is conceivable that a simpler calibrated routing approach could be suitable for flood forecasting purposes if starting from scratch, the existence of hydrodynamic models and associated data mean that this approach is justified if it can be delivered with the required computational stability and speed.

1.5 Consideration has been given to data requirements and availability

Q1.5.1 Have key data requirements (to cover hydrologic, hydraulic and geographical parameters) been identified?

- *Yes, hydrometric network is well known to the client and consultant.*

Q1.5.2 Have the required data been sourced? (By consultation with relevant Agency staff and/or external organisations and agencies where necessary).

- *Yes, many data are already available to the consultant from other studies.*

Q1.5.3 Have all available telemetry inputs been identified?

- *N/A for this project as the client will arrange implementation of the model for real-time use.*

Comment:
The hydrometry network for the Ouse system is well known to the consultant in this case. Significant previous work has been done to review the data sources.

Table 6.1: River Ouse case study – Milestone 1

1.6	**A fully documented preliminary model schematisation has been submitted, including a schematic of the main elements**
	Q1.6.1 Has a preliminary model schematic been produced and accepted by the client? • *N/A as the project builds on existing models.*
Comment: *In this case, the initial requirement was to understand the schematisation of the existing hydraulic models. However, the consultant reviewed the assumptions made in the existing model build and schematisation. The consultant geo-referenced the existing model data to assist with model review/ simplification and documentation.*	

Table 6.2: River Ouse case study – Milestone 2

MILESTONE 2. CONCEPTUALISATION AND CONFIGURATION	
2.1	**Appropriate software tools have been selected for model build**
	2.1.1 Is the software package (and version) to be used appropriate given the model requirements? • *Yes, ISIS v2.1 is EA Best Interim System (BIS) approved* 2.1.2 Is the software package (and version) compatible with NFFS and approved for use? • *Yes, model adapters available.* 2.1.3 Is the modeller aware of the weaknesses and drawbacks of the software? • *Yes, consultant and client are both experienced users.* 2.1.4 If a bespoke model is required, is this cost effective and justifiable? • *N/A*
Comment: *There was a clear agreement between client and consultant from the outset as to the required software tools for this work.*	
2.2	**Quality assurance procedures have been applied to input data**
	2.2.1 Have obtained data been documented in a project data register? • *Yes* 2.2.2 Has an audit of the quality/reliability of each input data set been carried out and documented? • *Yes, summarized in project final report. Also EA peer review of Skelton gauging station refers.* 2.2.3 Are methods used to manipulate data (if required) appropriate and acceptable? • *Little data processing required. Spreadsheet analysis OK.*
Comment: *A project data register was maintained to provide an audit trail. Data manipulation was limited mainly to storage and setting up model input files, rather than any processing of raw data (e.g. digitisation of survey drawings).*	
2.3	**The raw model meets the requirements of the brief**
	2.3.1 Does the model reflect the key features of the system, as identified in Protocol 1.3? • *Yes. (Raw model is in any case based on accepted HD models)*
Comment: *The project brief did not use the term 'raw model', but the initial combined and extended hydrodynamic model can be considered the 'raw model' for this project. It was later simplified and the calibration, accuracy and stability checked.*	
2.4	**The raw model meets a minimum quality standard**
	Q2.4.1 If the model has been discretised into separate subcatchments / reaches, have these been joined adequately? • *Yes, explicit joins in ISIS take account of backwater etc.* Q2.4.2 Is the model extent reasonable (i.e. how does the length of the modelled reach compare to the real river length)? • *Lengths correct. Downstream boundary condition is an observed tide gauge. Upstream boundaries are observed river gauges upstream of tidal limit.*

Table 6.2: River Ouse case study – Milestone 2

	Q2.4.3 Are the method(s) of defining model boundaries appropriate and have they been adequately documented? • *Yes, boundaries for calibration have been reviewed as reported in project record. Consideration was given to lateral inflows but these were thought negligible compared to the flow measured at the upstream gauging stations.* Q2.4.4 Are the method(s) used to define fixed/geometric model parameters appropriate and have they been adequately documented? • *Yes, derived from existing calibrated models.* Q2.4.5 Are rules for gate and barrage operation adequately documented and checked? • *Yes.* Q2.4.6 Has the modeller followed model/software specific guidelines where available (e.g. Guidelines for Acceptance of ISIS and Other Hydrodynamic Module Datasets for Flood Forecasting). • *Project completed before criteria available.*
Comment: *Given that the 'raw model' was in this case derived from existing models that had been tested and accepted by the client, the 'minimum quality standard' was considered to have been met.*	
2.5	**The resolution of the model is acceptable**
	Q2.5.1 Is there justification of the selected time step (is it small enough?) • *Fixed time step used for simulation in original raw model. Results available at 15-minute intervals – sufficient for forecasting on the Ouse.* Q2.5.2 Is the spatial resolution sufficient to represent key controls? • *Yes, supported by agreement with data and results of original (design) models.*
Comment: *Although the existing models, and hence the 'raw model', were built for design/planning use, the space and time resolution is at least sufficient for forecasting use.*	

Table 6.3: River Ouse case study – Milestone 3

MILESTONE 3. REVIEW	
3.1	**Model is parsimonious**
	Q3.1.1 Are time and spatial resolutions no more detailed than strictly necessary? • *Original 'raw model' does not run quickly enough for forecasting. Adequate run times and stable solution achieved using the simplified model.* Q3.1.2 Has a check been made for structures, junctions and controls that do not affect the forecast and can be removed from the model? • *Yes, reported in project record.* Q3.1.3 Has a check been made for any hydrodynamic reaches that can be simplified to routing reaches? • *No.* Q3.1.4 Has a check been made for any sub-catchments or reaches that can be combined? • *No.* Q3.1.5.Has a check been made for 'surplus' cross sections? • *Yes, some cross sections removed to produce simplified model.*
Comment: *Model simplification was a major aspect of this project and was reported in detail in the project records.*	
3.2	**Model is robust when simplified**
	Q3.2.1 Does decreasing the cross-section spacing reduce stability / accuracy? • *No.* Q3.2.3 Does the representation of floodplain storage affect the model stability or accuracy? • *Yes, stability problems associated with parallel channels resolved by representing floodplain areas using RESERVOIR units.* Q3.2.3 Does simplification of structures lead to a loss of stability or accuracy? • *No.*

Comment: *Mathematical stability was a key requirement of the project brief and was checked in detail.*	
3.3	**The model appears to run fast enough for real time use**
	Q3.3.1 Has the run time of the model been checked in relation to the required lead time? • *Run times meet stated requirement (less than 5-minutes for a simulation of a 48-hour forecast period on a machine with equivalent processing speed to the Compaq ProLiant DL580).*
Comment: *Run times were tested and documented in the project reports. Note that this was done off-line (i.e. not within the ultimate NFFS real-time platform) as required by the project brief.*	

Table 6.4: River Ouse case study – Milestone 4

MILESTONE 4. CALIBRATION AND VALIDATION	
4.1	**Calibration criteria are clear**
	Q4.1.1 Have locations used for calibration (e.g. forecast points / downstream boundary gauged data) been documented and agreed with the client? • *Yes: Viking Hotel, Foss confluence, Naburn Upstream, Wharfe Side at Cock Beck, Fleet Pumping Station, Cawood, Selby, Barmby Barrage (Ouse), Goole, Blacktoft, Carlton Bridge (Aire)* Q4.1.2 Have the criteria for calibration been documented and agreed (e.g. R2, visual fit, RMSE)? • *"Similar results (i.e. shape and magnitude of event level hydrograph) to those of the original Ouse model"* *Also used Nash and Sutcliffe efficiency.* Q4.1.3 What 'sensibility tests' are to be applied (e.g. channel capacity is sensible relative to median annual maximum flood)? • *None specified.*
Comment: *The calibration criteria were clearly defined and agreed by client and consultant. The criteria were not expressed simplistically as a target value of goodness-of-fit, but rather in terms of performance against various aspects of the hydrograph, including a requirement to pay particular attention to 'middle-order' events.*	
4.2	**Calibration and validation data are representative of operational conditions**
	Q4.2.1 Have you checked that the calibration data are of the same type and resolution as real-time data? • *Yes.* Q4.2.2 Is the calibration data of sufficient resolution to be able to resolve the features of the hydrograph that are of most relevance? • *Yes.* Q4.2.3 Are the flow conditions represented in the calibration data of sufficient range, given the scope of the model (including the effects of any artificial influences)? • *Yes*. Q4.2.4 Does the calibration data include at least one significant flood event (where flows are larger than QMED or out of bank)? • *Yes, more than one*. Q4.2.5 Has the quality of event data used in calibration been reviewed and accepted? • *Yes. Possible sources of hydrometric error reviewed in final report.* Q4.2.6 Where there are periods of missing data within calibration events, have appropriate decisions been taken and documented as to whether these should be infilled or whether the event should be rejected from the calibration? • *Linear interpolation for missing data*. Q4.2.7 Are calibration events representative of current catchment conditions? (Have there been any recent works or events in the catchment that may have modified the hydrologic / hydraulic regime)? • *Yes, events are representative.*

Table 6.4: River Ouse case study – Milestone 4

Comment: *The calibration and validation data were selected to encompass a range of flood events including multiple peaks.*	
4.3	**Performance of calibrated model is acceptable**
	Q4.3.1 Does the model fit the hydrograph peaks (magnitude and timing) and rising limb according to the agreed criteria? • *Yes. Average NSE > 0.8 for calibration and validation events.* Q4.3.2 Does the model also simulate the full flow range to an agreed standard of performance? • *Some errors in peak flow noted, but threshold crossings are accurately modelled.* Q4.3.3 Do the model outputs look reasonable at flows higher than the calibration event data? • *Not tested.* Q4.3.4 Are flood storage areas modelled adequately during a large or multi-peak event? • *Yes, e.g. Feb 2002 event.* Q4.3.5 Are there any unexplained headlosses (e.g. at structures) in the model results? • *Not checked.* Q4.3.6 Have the outputs been reviewed by Area of Regional staff with local knowledge? • *Model reviewed and accepted by regional forecasting team.*
Comment: *Ultimately this is a judgement call, but the main role of the Protocol here is to ensure that the reasons for accepting the calibrated model are documented and well understood. In this case, it is an ability to represent a range of historic events in terms of threshold crossing and peak levels and reproduction of results obtained from an existing, more detailed, design models.*	
4.4	**Model parameters are plausible and acceptable**
	Q4.4.1 Has the sensitivity of the model output to parameter values been evaluated? • *No.* Q4.4.2 Are the time delay and gain parameters plausible? • *N/A* Q4.4.3 Are the values of store depths and time constants physically realistic? • *N/A* Q4.4.4 Are wave speed and attenuation parameters realistic? • *N/A* Q4.4.5 Are roughness values realistic? • *Yes. Some problems noted in propagating low tide lower boundary conditions. Roughness values here may be having to compensate for changes in bed level since original survey (1967).* Q4.4.6 Does model attenuation match with actual? • *Yes, shown through calibration/validation performance especially with respect to threshold crossing times.* Q4.4.7 Are weir coefficients and bridge losses physically realistic? • *Yes.* Q4.4.8 Spill coefficients applied at washland and overland flow paths are realistic? • *Yes.*
Comment: *Parameter values audited in model check file. Some sensitivity tests carried out to roughness. Although it may have to be accepted that model parameters sometimes compensate for 'errors' in model structure or data errors, the consultant in this case did make and document checks on the plausibility of the main hydraulic parameters.*	
4.5	**Model performs well with validation data**
	Q4.5.1 Does the model perform to agreed and documented criteria for the validation event(s)? • *Yes.*
Comment: *As for calibration, the specification of test events and general criteria for acceptance of the model were clearly agreed.*	

Table 6.4: River Ouse case study – Milestone 4

4.6	**Limitations of validated model are understood and acceptable**
	Q4.6.1 Does the model perform sensibly when extrapolated to more extreme conditions? • *Not tested in calibration.* Q4.6.2 Has the EA project manager been advised of the limitations of the validated model? • *Yes, mainly relates to bed levels and quality of gauging station data.*
Comment: *General limitations of the ISIS modelling software were well known to both consultant and client. Some specific concerns were raised about the survey data on which the model is based (some of which dates back to 1967) and the quality of input data from the gauging station network. These issues were documented and the client is aware of them. The consultant also made some specific recommendations for improvements to the model should forecasts be needed on one reach where there is currently no forecast point.*	
4.7	**Calibration and validation procedures are well documented**
	Q4.7.1 Has a project report or record been delivered? • *Yes* Q4.7.2 Have documented model and data files been delivered? • *Yes*
Comment: *This is a straightforward check that all parties are clear that the definitive outputs of the calibration/validation stage have been delivered to the client with adequate documentation.*	

Table 6.5: River Ouse case study – Milestone 5

MILESTONE 5. TESTING	
5.1	**A plan for testing the model has been specified and agreed**
	Q5.1.1 Has a set of test runs been agreed & documented? • *Not required under contract – EA to undertake implementation in NFFS.*
5.2	**Model runs correctly in emulated real time forecasting network**
	Q5.2.1 Will the model run for calibration events in the test-control environment? • *N/A* Q5.2.2 Are the results in test –control environment the same as for off-line calibration or validation? • *N/A* Q5.2.3 Has the link between the model and other components of the network been checked? • *N/A* Q5.2.4 Can differences between model runs using actual and forecast data be explained? • *N/A*
5.3	**Model performance is stable in emulated real time use**

Table 6.5: River Ouse case study – Milestone 5

<table>
<tr><td colspan="2">Q5.3.1 Is the model robust to reasonably foreseeable drop-outs or errors in the input data (e.g. forecast rainfall, telemetry)?
• N/A
Q5.3.2 Do time-varying parameters change smoothly?
• N/A in this type of model.
Q5.3.3 Is the model stable for both cold and hot starts (i.e. for varying run-in times)?
• Not tested in emulated real-time setting.
Q5.3.4 Will the model run over a sufficiently wide range of flow conditions for real-time use?
• Not tested.
Q5.3.5 Is the river model stable for reasonably foreseeable start-up conditions?
• Yes.
Q5.3.6 Is the river model stable for reasonably foreseeable downstream boundary conditions?
• Yes, although some issues of model accuracy with low tide conditions were noted.
Q5.3.7 Are the lowest stable flows documented?
• No</td></tr>
<tr><td colspan="2">Comment:
The project brief did not include testing in emulated real time. However, the consultant did make specific recommendations that further tests of the delivered model should be undertaken to establish its operational limits in more detail than had been required within the project.</td></tr>
<tr><td>5.4</td><td>The model runs fast enough to achieve the required lead time</td></tr>
<tr><td colspan="2">Q5.4.1 Can the model provide the required lead time over a range of initial and input conditions?
• Yes – documented in final report for a computer platform equivalent to the target system.</td></tr>
<tr><td colspan="2">Comment:
Although the consultant was not required to test this within an emulated real-time environment, detailed tests were carried out to ensure that the model ran quickly enough to meet the eventual requirement of the client.</td></tr>
<tr><td>5.5</td><td>An updating or error predicting scheme is used if applicable</td></tr>
<tr><td colspan="2">Q5.5.1 Is state-updating used?
• N/A
Q5.5.2 Is error prediction used?
• N/A
Q5.5.3 Are updating or error prediction stable over a range of different events?
• N/A
Q5.5.4 If there is significant variation between consecutive forecast runs can this be explained by the error correction or updating procedures?
• N/A</td></tr>
<tr><td colspan="2">Comment:
These questions are not relevant to the modelling project considered here.</td></tr>
<tr><td>5.6</td><td>Operating uncertainties are documented</td></tr>
<tr><td colspan="2">Q5.6.1 Has the change in uncertainty with increasing lead time been checked?
• No
Q5.6.2 Are there features of the catchment that may introduce uncertainty because they cannot be modelled such as control structures not operating to prescribed rules or reservoir spills?
• None known
Q5.6.3 Have the operating uncertainties been documented in the project report?
• Main uncertainties relate to survey data and hydrometry – as documented.</td></tr>
<tr><td colspan="2">Comment:
Uncertainties arising from operational use of the model were not covered within the project brief. However, the consultant did comment on the most likely sources of error, which will relevant once the model is implemented in NFFS.</td></tr>
</table>

7 CASE STUDY EXAMPLE 2

7.1 Background

This chapter describes a second example application of the Modelling Protocols. This particular example uses a modelling project commissioned by North West Region of the Environment Agency, the objective of which was to add real time flood forecasting capability to the existing Section 105 and Flood Alleviation Scheme models of the River Eden. The modelling work was carried out by Eden Vale Modelling Services.

7.1.1 Study brief

The Agency's key requirements for the forecasting model were to enable timely and accurate flood warnings to be issued for the existing flood warning areas "the River Eden at Carlisle" (parts of the City of Carlisle that lie within these areas are vulnerable to flooding from a storm event as low as 1 in 5 years). Modelling was to make use of hydraulic and routing models constructed in previous flood risk mapping and other studies for the area.

7.1.2 Model detail

The flood forecasting model produced by the consultant in this case was delivered as a customised GIS application based on an underlying ISIS data set. Most of the model reaches are forecast using full hydrodynamic modelling although some flood routing reaches are employed. In addition gauged inflows are extended using transfer functions. Floodplain storage was treated explicitly within the model**.** Figure 7.1 shows a sketch of the modelled extent, summarising inputs to the model and flood warning areas.

The project was conducted in two phases – an initial model development in Phase 1, with revisions in Phase 2.

7.2 Application of Protocols for minimum standards

The following tables (Table 7.1 to Table 7.5) illustrate how the Protocols might have been completed for this example project. Answers to the supporting questions area based upon the consultant's Phase 2 Modelling Report and appendices, and have been completed as far as possible. It should therefore be noted that the project wasn't initially planned in accordance with the milestones set out in this report.

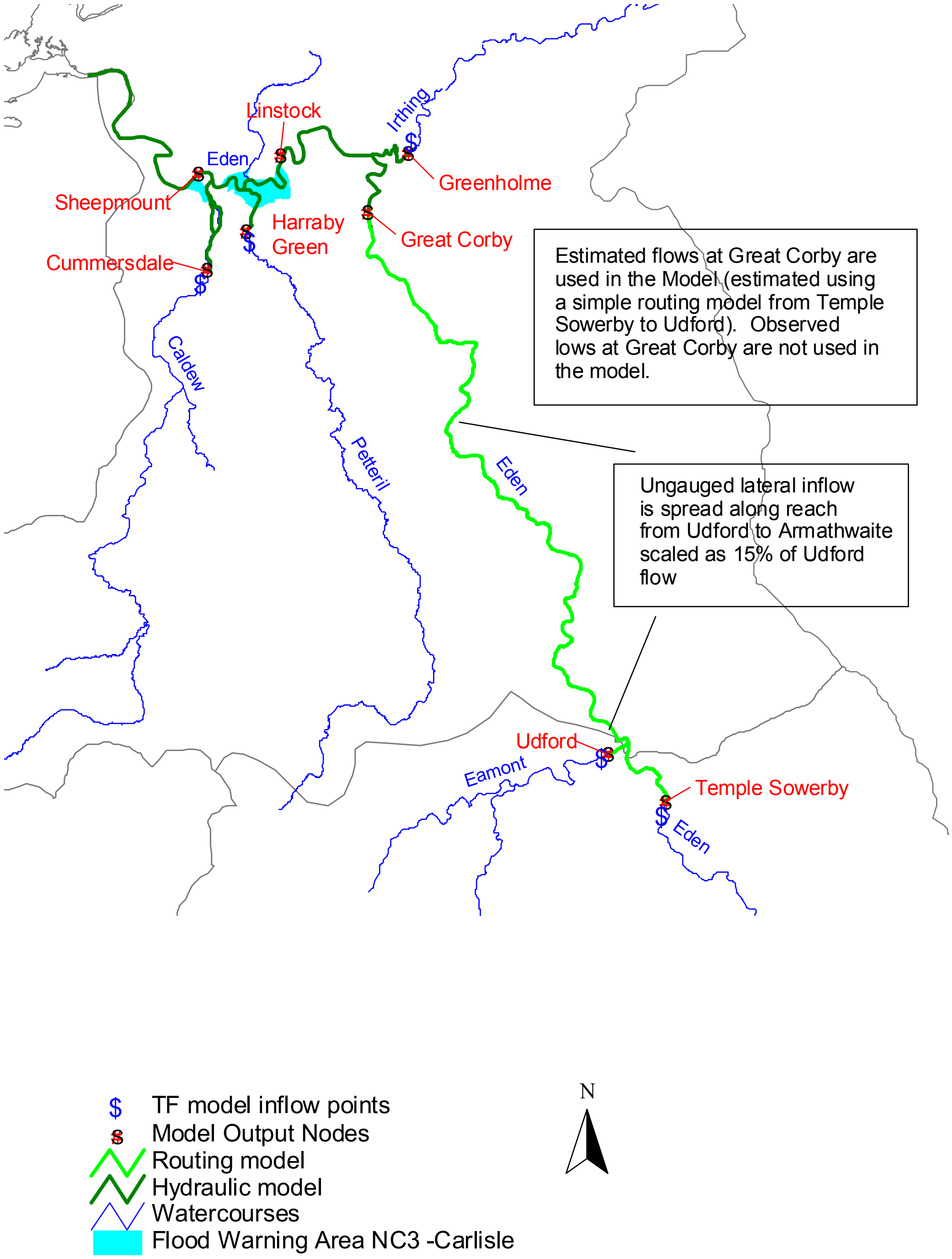

Figure 7.1: Schematic of Eden Real Time Isis Flood Forecasting Model (taken from a report by EdenVale Modelling Services, 2003).

Table 7.1: River Eden case study – Milestone 1

<table>
<tr><td colspan="2">MILESTONE 1. INCEPTION</td></tr>
<tr><td>1.1</td><td>The flood forecasting requirements are fully understood and agreed by both client and modeller</td></tr>
<tr><td></td><td>Q1.1.1 Are both parties clear regarding the operating platform / environment in which the model is to be run?
• Yes, it is to be capable for use with NW Region's existing systems.
Q1.1.2 Are both parties agreed on the level of sophistication of model required?
• Yes, modification of existing hydrodynamic models for real time use.
Q1.1.3 Have the forecast points and lead times required, and other performance criteria been agreed?
• Forecast locations were specified in project brief. Performance criteria are associated with timely and accurate flood warnings based on the forecast model.
Q1.1.4 Have target values for model resolution / accuracy been agreed, and what are the allowable tolerances?
• No specific target values set, but performance criteria associated with timely and accurate flood warnings based on the forecast model.
Q1.1.5 Has the use of real time updating/ error correction procedures been agreed?
• Updating was not included in the project brief.
Q1.1.6 Are both parties agreed about the data sources to be used for real time modelling?
• Yes, detailed review of hydrometric data was carried out in Phase 1 of project.</td></tr>
<tr><td colspan="2">Comment:
The main requirements of the project in this case are for delivery of a hydrodynamic model for forecasting (in order to incorporate flood storage). Implementation in a real-time forecasting environment is to be undertaken by the client, not the consultant. However the consultant developed a GIS based interface for the model to be used on the clients system.</td></tr>
<tr><td>1.2</td><td>Consideration has been given to previous work / models and their implications</td></tr>
<tr><td></td><td>Q1.2.1 Have existing hydrologic/hydraulic models relevant to the study area been identified?
• Existing ISIS models: De Leuw Rothwell (DLR) Section 105 model (interim and final versions).
Q1.2.2 Have the quality of existing models and the data on which they are based been examined, documented and any potential problems highlighted?
• Not explicitly discussed in the Phase 2 report.
Q1.2.3 Have any weaknesses of existing models and/or modelling approaches been identified and documented?
• Not explicitly discussed in the Phase 2 report.
Q1.2.4 If parts of existing models are being reused, have they been thoroughly checked (e.g. cross section data is up to date)?
• The models have been checked during Phase 1 of this project.</td></tr>
<tr><td colspan="2">Comment:
The project brief was to modify S105 models for real time use, therefore this Protocol is highly significant. The original model was discussed in the Phase 1 Report available from the project manager (Tilak Peiris, NW).</td></tr>
<tr><td>1.3</td><td>Consideration has been given to which particular catchment features are significant</td></tr>
</table>

Table 7.1: River Eden case study – Milestone 1

	Q1.3.1 Backwater effects • *Yes, hydrodynamic model.* Q1.3.2 Floodplain storage • *Yes, were represented by ISIS reservoir units with dimensions based on LiDAR data.* Q1.3 3 Confluences • *Yes, represented explicitly.* Q1.3.4 Tidal influences • *N/A* Q1.3.5 Typical speed of response in the catchment • *The Phase 2 report does not explicitly refer to any tests for this.* Q1.3.6 Typical bed slope • *Accounted for in ISIS model.*
	Q1.3.7 Snowmelt • *N/A* Q1.3.8 Groundwater and surface water interactions • *N/A* Q1.3.9 Abstractions and discharges • *Not included, unknown whether any significant in catchment.* Q1.3.10 Intakes and flood relief channels • *Not included, unknown whether any significant in catchment.* Q1.3.11 Reservoirs and lakes • *N/A* Q1.3.12 Sluices, gates – operational rules • *Included as necessary* Q1.3.13 Bridges and culverts causing significant constriction or afflux • *Represented in original models S105 models* Q1.3.14 Urbanisation • *N/A*
Comment:	
1.4	**The proposed modelling approach is justified**
	Q1.4.1 Is the proposed modelling approach broadly applicable, given the flood forecasting requirements? • *Yes, the requirement was for a real-time HD model.* Q1.4.2 Is the proposed approach suitable given the hydrologic and hydraulic characteristics of the river / catchment? • *Yes, significant floodplains storage means that a HD model is a justifiable option.* Q1.4.3 If a hybrid approach is used, has thought been given to the consistency of the different elements? • *Transfer function modelling is used to produce forecasts at gauged inflow points, this was successfully incorporated in the HD model.* Q1.4.4 Can the data requirements of the proposed modelling approach be met? • *Yes, existing models and hydrometric data are available from the Environment Agency.* Q1.4.5 Are appropriate tools available to build and calibrate the proposed type of model? • *Yes, ISIS software* Q1.4.6 Are the assumptions and uncertainties of the approach recognised and documented? • *Yes, requirement for accurate survey data, representation of structures and hydrometric data.*
Comment: *Floodplain storage is significant within the Eden Valley, and for this reason a HD approach is appropriate. The Phase 1 model was revised in Phase 2 to improve the representation of such areas within the model. Furthermore, there was an existing hydrodynamic model (and associated data).*	

Table 7.1: River Eden case study – Milestone 1

1.5	**Consideration has been given to data requirements and availability**
	Q1.5.1 Have key data requirements (to cover hydrologic, hydraulic and geographical parameters) been identified? • *Yes* Q1.5.2 Have the required data been sourced? (By consultation with relevant Agency staff and/or external organisations and agencies where necessary). • *Yes, many data were already available to the consultant from the S105 model.* Q1.5.3 Have all available telemetry inputs been identified? • *The model is based real-time observed data in WRIP.*
Comment:	
1.6	**A fully documented preliminary model schematisation has been submitted, including a schematic of the main elements**
	Q1.6.1 Has a preliminary model schematic been produced and accepted by the client? • *N/A as the project builds on existing models.*
Comment: *In this case, the initial requirement was to understand the schematisation of the existing hydraulic models, and to consider the main implications of updating these for use on a real-time basis.*	

Table 7.2: River Eden case study – Milestone 2

MILESTONE 2. CONCEPTUALISATION AND CONFIGURATION	
2.1	**Appropriate software tools have been selected for model build**
	2.1.1 Is the software package (and version) to be used appropriate given the model requirements? • *Yes, ISIS is EA Best Interim System (BIS) approved.* 2.1.2 Is the software package (and version) compatible with NFFS and approved for use? • *Model not to be used with NFFS, rather to be utilised within NW Region's existing flood forecasting capability.* 2.1.3 Is the modeller aware of the weaknesses and drawbacks of the software? • *Yes, consultant and client are both experienced users.* 2.1.4 If a bespoke model is required, is this cost effective and justifiable? • *N/A*
Comment: *There was a clear agreement between client and consultant from the outset as to the required software tools for this work.*	
2.2	**Quality assurance procedures have been applied to input data**
	2.2.1 Have obtained data been documented in a project data register? • *Not known* 2.2.2 Has an audit of the quality/reliability of each input data set been carried out and documented? • *Phase 2 report refers to audit of input data sets, such as the Greenholme stage-discharge relationship.* 2.2.3 Are methods used to manipulate data (if required) appropriate and acceptable? • *Methods used not discussed in detail in Phase 2 report, but appear to be appropriate giving acceptable results.*
Comment:	
2.3	**The raw model meets the requirements of the brief**
	2.3.1 Does the model reflect the key features of the system, as identified in Protocol 1.3? • *The Raw model can be thought of as the Initial Phase 1 model, prior to calibration. As this is strongly based on an accepted HD model, the answer is yes.*

Table 7.2: River Eden case study – Milestone 2

Comment: *Note that the Phase 1 model was later improved and revised after a "review" process, and reported under Phase2.*	
2.4	**The raw model meets a minimum quality standard**
	Q2.4.1 If the model has been discretised into separate subcatchments / reaches, have these been joined adequately? • *Yes, explicit joins in ISIS take account of backwater etc.* Q2.4.2 Is the model extent reasonable (i.e. how does the length of the modelled reach compare to the real river length)? • *Upstream model boundaries are reasonable. Downstream boundary condition not discussed in Phase 2 Report.* Q2.4.3 Are the method(s) of defining model boundaries appropriate and have they been adequately documented? • *Yes, upstream boundaries are real-time gauging sites, detailed consideration given to smaller tributaries and lateral inflows.* Q2.4.4 Are the method(s) used to define fixed/geometric model parameters appropriate and have they been adequately documented? • *Yes, derived from existing calibrated models.* Q2.4.5 Are rules for gate and barrage operation adequately documented and checked? • *N/A* Q2.4.6 Has the modeller followed model/software specific guidelines where available (e.g. Guidelines for Acceptance of ISIS and Other Hydrodynamic Module Datasets for Flood Forecasting). • *Project completed before criteria available.*
Comment: *Given that the 'raw model' was in this case derived from existing models that had been tested and accepted by the client, the 'minimum quality standard' was considered to have been me. Implications of real time use had been considered and addressed.*	
2.5	**The resolution of the model is acceptable**
	Q2.5.1 Is there justification of the selected time step (is it small enough?) • *A time step of 150 seconds was used in this model. This is a balance between stability of model and performance, and is discussed and justified in the Phase 2 report.* Q2.5.2 Is the spatial resolution sufficient to represent key controls? • *Yes, supported by agreement with data and results of original (design) models.*
Comment: *The time step of the model has been carefully considered, as discussed in the Phase 2 Report.*	

Table 7.3: River Eden case study – Milestone 3

MILESTONE 3. REVIEW	
3.1	**Model is parsimonious**
	Q3.1.1 Are time and spatial resolutions no more detailed than strictly necessary? • *Removal of key structures that have negligible effect on forecasts allowed increase in model time step.* Q3.1.2 Has a check been made for structures, junctions and controls that do not affect the forecast and can be removed from the model? • *Yes, reported in project record, especially around the Little Caldew.* Q3.1.3 Has a check been made for any hydrodynamic reaches that can be simplified to routing reaches? • *No.* Q3.1.4 Has a check been made for any sub-catchments or reaches that can be combined? • *Opposite action required – addition of explicit reservoir units to represent floodplain storage.* Q3.1.5.Has a check been made for 'surplus' cross sections? • *Yes, some cross sections removed to improve stability – documented in final report.*

Comment: *Model was changed to improve stability and robustness, rather than with the explicit aim of simplification. Some additional units considered necessary to represent floodplain storage.*	
3.2	**Model is robust when simplified**
	Q3.2.1 Does decreasing the cross-section spacing reduce stability / accuracy? • *Not tested.* Q3.2.3 Does the representation of floodplain storage affect the model stability or accuracy? • *Not reported.* Q3.2.3 Does simplification of structures lead to a loss of stability or accuracy? • *Noted in final report that removal of one weir improved stability, allowing the time step of model runs to increase up to 300 and 600 seconds over parts of the hydrograph. It was found that these higher time steps produce differing results from the VPMC reaches particularly upstream of Great Corby. The differences were found to be negligible below 150 seconds. The runs were therefore repeated with a maximum time step of 150 seconds. It was recommended that the maximum time step for operational forecasting also be set to 150 seconds based on these findings.*
Comment: *Mathematical stability was checked.*	
3.3	**The model appears to run fast enough for real time use**
	Q3.3.1 Has the run time of the model been checked in relation to the required lead time? • *Model runs to forecast lead time of four hours.*
Comment: *Computational run times not specified in the modelling report, but the requirement is for a lead time of 4 hours.*	

Table 7.4: River Eden case study – Milestone 4

MILESTONE 4. CALIBRATION AND VALIDATION	
4.1	**Calibration criteria are clear**
	Q4.1.1 Have locations used for calibration (e.g. forecast points / downstream boundary gauged data) been documented and agreed with the client? • *Yes: Great Corby gauging station (stage record) and Sheepmount gauging station (stage).* Q4.1.2 Have the criteria for calibration been documented and agreed (e.g. R^2, visual fit, RMSE)? • *The criteria used in this case were the shape, size and timing of the hydrograph peaks for a number of simulated flood events occurring during the last 10 years.* Q4.1.3 What 'sensibility tests' are to be applied (e.g. channel capacity is sensible relative to median annual maximum flood)? • *None specified.*
Comment: *The calibration criteria were clearly defined and agreed by client and consultant. The criteria were not expressed simplistically as a target value of goodness-of-fit, but rather in terms of performance against various aspects of the hydrograph (i.e. agreement with hydrograph shape, accuracy of peak estimate (in m) accuracy of timing of peak (in hours).*	
4.2	**Calibration and validation data are representative of operational conditions**

Table 7.4: River Eden case study – Milestone 4

	Q4.2.1 Have you checked that the calibration data are of the same type and resolution as real-time data? • *Yes.* Q4.2.2 Is the calibration data of sufficient resolution to be able to resolve the features of the hydrograph that are of most relevance? • *Yes.* Q4.2.3 Are the flow conditions represented in the calibration data of sufficient range, given the scope of the model (including the effects of any artificial influences)? • *The model and the data used to calibrate it are flood flow data and will not apply when the flow in the river approaches baseflow conditions.* Q4.2.4 Does the calibration data include at least one significant flood event (where flows are larger than QMED or out of bank)? • *The calibration events include a range of flood events, some of greater severity than others.* Q4.2.5 Has the quality of event data used in calibration been reviewed and accepted? • *Not explicitly discussed in the Phase 2 Report.* Q4.2.6 Where there are periods of missing data within calibration events, have appropriate decisions been taken and documented as to whether these should be infilled or whether the event should be rejected from the calibration? • *Not clear from Phase 2 Report.* Q4.2.7 Are calibration events representative of current catchment conditions? (Have there been any recent works or events in the catchment that may have modified the hydrologic / hydraulic regime)? • *Yes, calibration events are representative.*
Comment: *The calibration data were selected to encompass a range of flood events.*	
4.3	**Performance of calibrated model is acceptable**
	Q4.3.1 Does the model fit the hydrograph peaks (magnitude and timing) and rising limb according to the agreed criteria? • *Yes. Magnitude typically within +0.04 to +0.09m.* Q4.3.2 Does the model also simulate the full flow range to an agreed standard of performance? • *As noted earlier, the model does not perform well when flows approach baseflow levels.* Q4.3.3 Do the model outputs look reasonable at flows higher than the calibration event data? • *Not tested.* Q4.3.4 Are flood storage areas modelled adequately during a large or multi-peak event? • *Not explicitly reported.* Q4.3.5 Are there any unexplained headlosses (e.g. at structures) in the model results? • *None reported.* Q4.3.6 Have the outputs been reviewed by Area of Regional staff with local knowledge? • *Model reviewed and accepted by regional forecasting team.*
Comment: *The Phase 2 Report does not report the full range of calibration tests that were carried out. Some validation tests were reported with a recommendation for further validation.*	

Table 7.4: River Eden case study – Milestone 4

4.4	**Model parameters are plausible and acceptable**
	Q4.4.1 Has the sensitivity of the model output to parameter values been evaluated? • *No.* Q4.4.2 Are the time delay and gain parameters plausible? • *N/A* Q4.4.3 Are the values of store depths and time constants physically realistic? • *N/A* Q4.4.4 Are wave speed and attenuation parameters realistic? • *N/A* Q4.4.5 Are roughness values realistic? • *Some roughness parameters were changed between Phase 1 and Phase 2 to improve the model.* Q4.4.6 Does model attenuation match with actual? • *Yes, shown through the fact that peaks are well modelled and threshold crossing times seem to be modelled with good accuracy.* Q4.4.7 Are weir coefficients and bridge losses physically realistic? • *Yes.* Q4.4.8 Spill coefficients applied at washland and overland flow paths are realistic? • *Use of spill units was carefully considered, especially at reservoir units.*
Comment: *Did not have access to model data file.*	
4.5	**Model performs well with validation data**
	Q4.5.1 Does the model perform to agreed and documented criteria for the validation event(s)? • *Yes.*
Comment: *As commented earlier the Phase 2 report recommended further validation is carried out in future phases of the project.*	
4.6	**Limitations of validated model are understood and acceptable**
	Q4.6.1 Does the model perform sensibly when extrapolated to more extreme conditions? • *Not tested in calibration.* Q4.6.2 Has the EA project manager been advised of the limitations of the validated model? • *Yes, the limitations of the model are discussed in detail in the Phase 2 report.*
Comment: *Also general limitations of the ISIS modelling software were well known to both consultant and client.*	
4.7	**Calibration and validation procedures are well documented**
	Q4.7.1 Has a project report or record been delivered? • *Yes* Q4.7.2 Have documented model and data files been delivered? • *Yes*
Comment:	

Table 7.5: River Eden case study – Milestone 5

MILESTONE 5. TESTING	
5.1	**A plan for testing the model has been specified and agreed**
	Q5.1.1 Has a set of test runs been agreed & documented? • *The GIS user interface supplied with the model allows the model to be readily applied in real time. The model has been implemented in practice for the last year and has been found to be working well.*

Table 7.5: River Eden case study – Milestone 5

5.2	**Model runs correctly in emulated real time forecasting network**
	Q5.2.1 Will the model run for calibration events in the test-control environment? • *N/A* Q5.2.2 Are the results in test –control environment the same as for off-line calibration or validation? • *N/A* Q5.2.3 Has the link between the model and other components of the network been checked? • *N/A* Q5.2.4 Can differences between model runs using actual and forecast data be explained? • *N/A*
5.3	**Model performance is stable in emulated real time use**
	Q5.3.1 Is the model robust to reasonably foreseeable drop-outs or errors in the input data (e.g. forecast rainfall, telemetry)? • *At present, observed data is required for all upstream inflow sites, and forecasts will not continue if one of these key stations is not available. Data redundancy scenarios can be specified, but utilisation of this facility is still under consideration by the EA.* Q5.3.2 Do time-varying parameters change smoothly? • *N/A* Q5.3.3 Is the model stable for both cold and hot starts (i.e. for varying run-in times)? • *N/A* Q5.3.4 Will the model run over a sufficiently wide range of flow conditions for real-time use? • *The model has been used in practice for over three years.* Q5.3.5 Is the river model stable for reasonably foreseeable start-up conditions? • *Yes. The model has been used in practice for over three years.* Q5.3.6 Is the river model stable for reasonably foreseeable downstream boundary conditions? • *This issue is not explicitly discussed in the Phase 2 Report.* Q5.3.7 Are the lowest stable flows documented? • *Yes.*
Comment: *The project brief did not include testing in emulated real time. However, the consultant did make specific recommendations that further tests of the delivered model should be undertaken to establish its operational limits in more detail than had been required within the project.*	
5.4	**The model runs fast enough to achieve the required lead time**
	Q5.4.1 Can the model provide the required lead time over a range of initial and input conditions? • *Yes – the Phase 2 documentation reports very good lead times (up to 12 hours in some scenarios).*
Comment: *The model has been used in a real-time environment for some time.*	
5.5	**An updating or error predicting scheme is used if applicable**
	Q5.5.1 Is state-updating used? • *N/A* Q5.5.2 Is error prediction used? • *N/A* Q5.5.3 Are updating or error prediction stable over a range of different events? • *N/A* Q5.5.4 If there is significant variation between consecutive forecast runs can this be explained by the error correction or updating procedures? • *N/A*
Comment: *These questions are not relevant to the modelling project considered here.*	

Table 7.5: River Eden case study – Milestone 5

5.6	**Operating uncertainties are documented**
	Q5.6.1 Has the change in uncertainty with increasing lead time been checked? • *No* Q5.6.2 Are there features of the catchment that may introduce uncertainty because they cannot be modelled such as control structures not operating to prescribed rules or reservoir spills? • *None known.* Q5.6.3 Have the operating uncertainties been documented in the project report? • *Yes, these are discussed in detail in the Phase 2 report.*
Comment: The model has been used in a real-time environment for the past year. This has led to a number of issues being identified, which are discussed in detail in the report. A number of recommendations have been given to how the model might be improved in the future in order to resolve these issues.	

8 SUMMARY AND RECOMMENDATIONS

8.1 Clarity of purpose

It was clear from the consultation stage of this project that there is not a complete consensus view about the need for and form of ‘modelling Protocols’ amongst modellers and project managers within the flood forecasting business. Nor is the concept of ‘Protocols’ always understood in the same way. It is therefore essential that the Protocols reported in this project are presented with a very clear statement of their intended purpose. This should make it clear that the Protocols are intended to help create *minimum* standards in modelling, and that experienced modellers may well already exceed this requirement. It should be made clear that the Protocols are to be used as a project management tool to provide a consistent way of documenting the most critical aspects of each of the generic stages of the modelling project.

8.2 Ownership

The Protocols for minimum standards now exist as an output of this R&D project, both as a checklist of questions presented in this report and as an interactive Word proforma that can be used by project managers and modellers. However, the Protocols will not necessarily be taken up in practice if they remain as outputs of the R&D programme only. There needs to be a policy on their use (see below) and a mechanism for disseminating the R&D outputs and raising awareness. In addition, the Protocols should be reviewed and updated as experience is gained in their use on projects.

These steps, which will lead to successful uptake of the Protocols, require above all that there is clear and active ownership of the Protocols within the Agency’s forecasting business. We recommend that the Protocols are ‘owned’ by the National Flood Forecasting Group, as this group would also decide on policy for use. The ‘owner’ of the Protocols should be clearly identified on the documents themselves, as is the case with the Agency’s flood risk mapping specification.

8.3 Policy on use

8.3.1 Requirement to apply Protocols

It is essential that a policy on use of the Protocols is established by the Agency. Given that we found widely varying views on the need for and form of the Protocols amongst informed professionals, we would recommend that great care is taken in drafting the usage policy to ensure that experienced modellers and project managers do not feel that the Protocols are merely imposing a layer of red tape. The policy on use should be clear that the reasons for applying the Protocols are to create:

- consistency of QA documentation across the Agency and over time, and
- documented evidence of reaching an agreed minimum standard in forecasting modelling projects.

8.3.2 Compliance

It should be made clear that the Protocols are not intended to serve as guidance on modelling methods (there may be numerous alternative ways of 'passing' each Protocol). It should also be clear that completion of the Protocols is worthwhile in providing a clear, consistent record of the modelling project even if this may seem to be 'overkill' at the time the work is carried out. The emphasis should be firmly on documentation and consistency.

Use of the Protocols should be made a condition of contract specifications for forecasting work. However, it should be left to the discretion of the project manager whether to require each Protocol to be completed separately as a distinct stage in the modelling process, or whether to group stages and Protocols together. This follows from the view that the Outline Modelling Specification (OMS) and the five-stage modelling strategy are idealised, whereas most projects exist within the context of previous work and the background experience of client and consultant teams, two factors that explain the variations between actual project specifications when compared with the OMS.

The assessment of 'compliance' for each Protocol may be difficult in some cases. This is to be expected; modelling practice is not standardised, and arguably never can be. For this reason, the Protocols proposed here avoid setting absolute standards for parameters, 'accuracy' etc. These are defined already in Agency specifications (particularly the flood mapping specification). Instead, compliance with the Protocols should be judged on whether checks have been carried out and reported, whether exceptions to specified standards are noted and explained and, ultimately, whether a model performs to the requirements of the project.

Perhaps the most contentious issue will be the policy on what to do when one or more Protocols are not 'passed' during a modelling project. It is suggested that there should not be a policy of automatically rejecting a forecasting model because it does not meet the minimum standards in the Protocols. This would be too restrictive in view of the varied challenges faced by modelling teams. However, failure to pass one of the modelling Protocols should be noted within project records and some explanation given as the to reason the 'failure' is not considered critical.

8.4 Dissemination

The Protocols can be made available via the Agency's interim library of electronic outputs for the joint Defra/EA Flood and Coastal Erosion Research Programme. The NFFG should be used to brief Agency forecasting teams about their existence. Other useful methods of dissemination will be to make the Protocols available via the Agency intranet and also to publish them on the Strategic Flood Risk Management Framework website for consultants to download. They may also be publicised through a paper at the next Defra conference.

8.5 Involvement of Area staff

One of the points raised by some respondents to our consultation was that Environment Agency staff from Area offices, or with specific catchment responsibilities should be closely involved in the modelling process. One convenient way to achieve this aim would be to ensure that the Modelling Protocols are circulated, along with any reports, project notes etc. on completion of each stage of the modelling project. In effect, the local staff would then have the opportunity to 'approve' the Protocols, based on their detailed knowledge of a catchment.

It may be particularly valuable to allow local staff the opportunity to play this review role at the inception and review stages of the project, where their comments could help prevent a model being developed that missed key features of the catchment. Area staff might have less input at the calibration and test-controlling stages, where the issues are more closely related to the mechanics of modelling and running models within the real-time environment.

8.6 Outline Modelling Specification

The Outline Modelling Specification presented as Appendix 3 of this report attempts to provide a basis for contract specifications that would deliver on the modelling strategy outlined in Chapter 1. It has been compiled using a number of earlier documents that have been circulated within the Environment Agency. The revised OMS collates material from these sources, but it is noted that there has not been a single, unique view on the appropriate division of modelling tasks into stages within the existing documentation. Modelling is not a production line process and we do not feel that imposing a single 'OMS' prescriptively on future forecasting projects would be desirable or even possible. Instead, the OMS should be viewed as a 'menu' of important activities, structured in such as way as to conform to the main stages in the modelling process proposed in Chapter 4 of this report. Individual project specifications may be able to use or adapt parts of the OMS, but it should always be possible to vary contract specifications according to circumstances.

8.7 Further research

The Protocols reported here concentrate on fluvial flood forecasting using one-dimensional river models. Parallel quality checks should be developed for coastal and estuary forecasting and for 2-D modelling. These should be packaged in a coherent way to build up a single QA approach. This may be done within the framework of a 'model management tool', building on the type of software being developed within the HarmoniQuA project. Further work would be needed to take these European project outputs and incorporate the QA Protocols specific to flood forecasting practice within the Agency.

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APPENDIX 1 – CONSULTATION QUESTIONNAIRE

R&D W5C-021

Protocols for minimum standards in modelling

Consultation questionnaire

June 2004

Aims of the consultation

The Environment Agency has recently commissioned R&D project W5C-021 to develop protocols for "minimum standards in modelling". These protocols will provide a formalised procedure, to be used in the course of commissioning or adapting a river model for flood forecasting, for reviewing the robustness of the model building and testing cycle. This will ultimately help project managers to guide modelling projects towards adopting good standards.

It has been decided that project managers, modellers and others involved in the Agency's flood forecasting and warning business should be consulted about the form and use of modelling protocols. We are therefore circulating this Consultation Questionnaire as a way of canvassing the views of key staff. Please use it to tell us how you think modelling practice could be improved by answering the 16 short questions as fully as possible.

Background

As shown in Figure 1, the protocols will provide one component in an overall approach to quality assurance and audit of modelling practices, which also includes provision of guidance on choice of model[1] and Generic Performance Measures[2] (both developed under separate R&D projects).

The protocols will specifically apply to model building, verification and testing, where it is intended that they will be used to critically review the decisions made and activities undertaken by the modeller(s).

The protocols will therefore have four main roles:

i) To ensure agreement between the modeller and project manager with regard to what the modelling must deliver.
ii) To ensure agreement between the modeller and project manager with regard to what tasks need to be undertaken during each part of the modelling process.
iii) To ensure that each of the agreed tasks is undertaken and completed appropriately.
iv) To ensure that there has been adequate documentation throughout.

The model building process includes a number of stages, the completion of which mark milestones in the modelling project cycle. Figure 2 summarises these stages and the main tasks within each, as proposed in the National Flood Forecasting System Strategy. There will be a Generic Modelling Specification to provide guidance on meeting these milestones. The protocols will apply at each stage to formalise the milestones, and it is anticipated that they must be "checked-off" or approved by project managers before modellers proceed to the next stage. This means that each protocol will be required to address a combination of generic and specific issues, depending on the relevant stage in the model building process, the modelling approach being used and the terms of reference of the project.

[1] Tilford, K.A., Sene, K., Chatterton, J.B. and C Whitlow, C. 2003. Flood Forecasting - Real Time Modelling. EA R&D Technical Report W5C-013/5/TR.
[2] Project W5C-021 Generic Performance Measures (Flood Warning Management System Phase 2b).

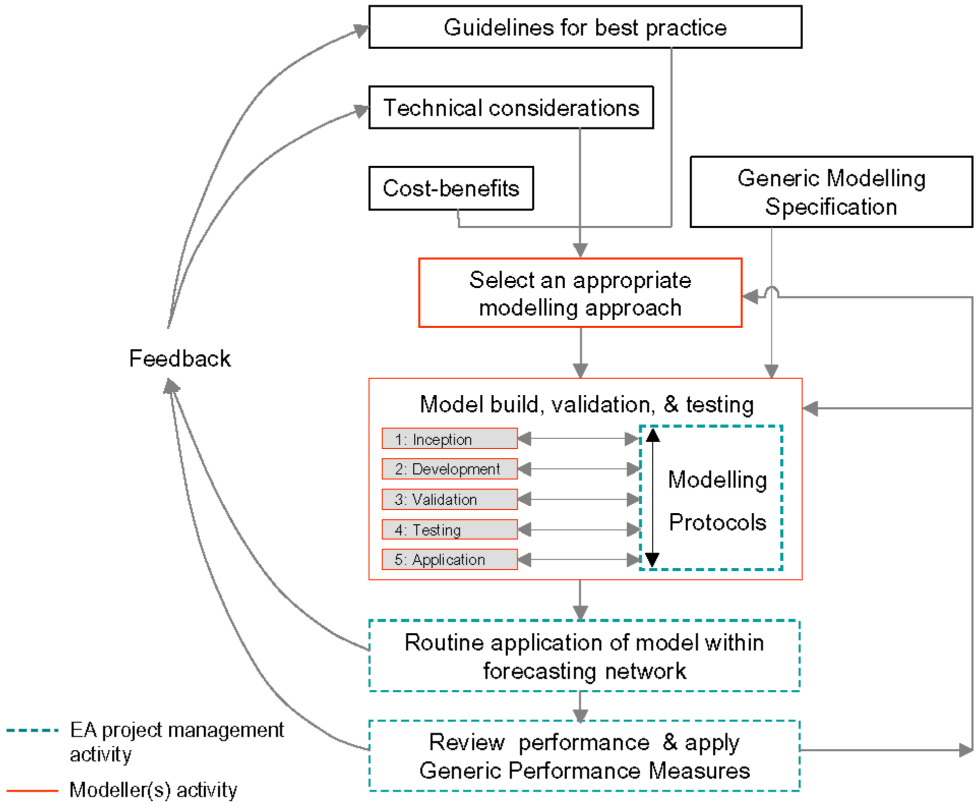

Figure 1. Proposed role of modelling protocols in quality assurance of flood forecasting models.

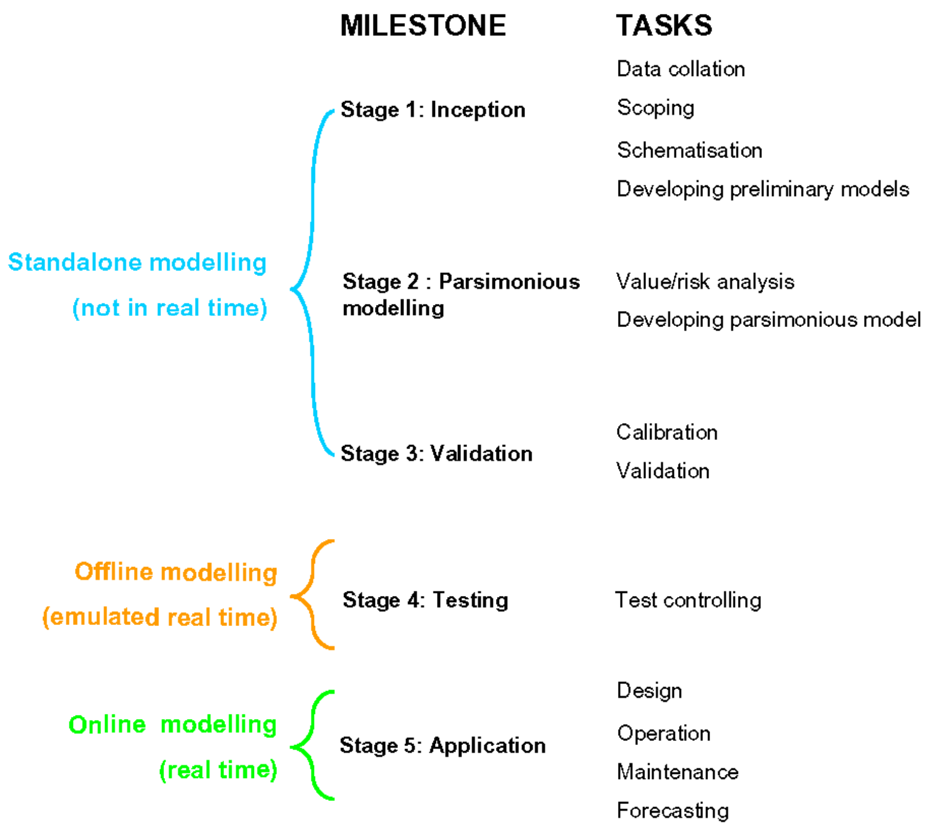

Figure 2. Stages in the model building and testing cycle for flood forecasting models proposed by the National Flood Forecasting Systems Strategy.

PART 1: Current practice

In this section we ask about your experiences and problems encountered when commissioning flood forecasting models. Please note that the content of this form will be treated in the strictest confidence and in accordance with the Data Protection Act. The information you provide will not be attributable directly to you without your permission. The contact details will not be used for any other purpose or divulged to any other party.

Q1. Please enter your details.	
Name:	
Job Title:	
Organisation:	
Address:	
Country:	
Tel No.:	
Fax No.:	
E-mail:	

Q2. Would you be happy to be acknowledged in the final project reports as a respondent to this consultation?	Please tick
Yes	
No	

Q3. What is (are) your main role(s) within the flood forecasting business?		Please tick
A	Agency project manager	
B	Agency modeller	
C	Consultant modeller	
D	Other (please state)	

Q4. What do you see as the main problems encountered when developing models to be used for flood forecasting, and what possible solutions might be envisaged?

Q5. In your experience, how well does current practice correspond to the five-stage process illustrated in Figure 2? What tasks are normally carried out at each stage?

PART 2: Use of modelling protocols

The aim of these questions is to determine how you think the protocols might best be used to help you deliver flood forecasting models.

Q6. How will protocols help you to deliver your flood forecasting models?

Q7. How should the protocols be applied?

		Please tick
A	As a checklist	
B	As open questions	
C	By the modeller	
D	By the client / EA project manager	
E	Other (please state)	

Q8. Please explain the reasons for your answer to Q7. Please tick

Q9. What form should 'modelling protocols' take to be most readily used?		Please tick
A	Paper notes	
B	Standard pro-forma as MS Word document	
C	Standard pro-forma as MS Excel Spreadsheet	
D	Database application	
E	Standard pro-forma as Adobe PDF	
F	Web-based form	
G	If you have used 'protocols' in the past, what format did they take, and how well did this approach perform?	
H	Please mention any other ideas for possible forms of modelling protocols.	

Q10. How much and what type of guidance should accompany the protocols?		Please tick
A	No guidance required	
B	Written guidance	
C	Worked example	
D	Training workshop	
E	On-line help facility / tutorial	
F	Other (please give details)	

Q11. Who should take responsibility for enforcing the protocols?		Please tick
A	Should not be enforced	
B	The Policy Team	
C	The Process Team	
D	Joint responsibility between Policy and Process Team	
E	The NFFG	
F	Pre-designated person in each region	
G	Out-sourced	
H	Other (please give details)	

Q12. Who should own and update the protocols as they change in the future?		Please tick
A	Should not be updated	
B	The Policy Team	
C	The Process Team	
D	Joint responsibility between Policy and Process Team	
E	The NFFG	
F	Other (please give details)	

PART 3: Content of protocols

The aim of these final four questions is to determine what you would like the protocols to cover.

Q13. What generic topics should the protocols cover?

		Please tick
A	The purpose of the modelling study / Terms of Reference	
B	The main features of the catchment (or coastline) that influence flood risk	
C	Accuracy of input data and procedures for assessing this	
D	Appropriateness of various modelling solutions	
E	The reasons for adopting the chosen modelling solution	
F	The assumptions of the chosen model	
G	Testing whether any additional functions or components should be considered for addition to the model.	
H	Testing whether any additional functions or components should be considered for removal from the model.	
I	Procedures used in calibration of the model	
J	Procedures used in validation of the model	
J	Range of applicability of the model (consideration of specific conditions under which the model may fail or become less accurate)	
K	Stability and robustness of the model	
L	Real-time testing of the model	
M	Documentation of the model development	
N	Documentation of the model	
O	Please state any other suggestions	

Q14. If topics are to be specific as well as generic, to which types of models should they apply? Please rank in order where 1= highest		
A	Level correlation	
B	Time of travel relationships	
C	Rainfall-runoff models	
D	Hydrological routing models	
E	1-D hydrodynamic models	
F	2-D hydrodynamic models	
G	3-D hydrodynamic models	
H	Transfer function models	
I	Please state any other suggestions	
J	Please give any other comments on how protocols might be applied to the different model types	

Q15. Should the protocols be used as the basis of a standardised form of summary documentation?

		Please tick
A	Yes	
B	No	
C	Please state the reasons for your choice.	

Q16. If the protocols were to provide the basis of a standardised form of summary documentation, which of the following should be included?

		Please tick
A	A map of the proposed model network	
B	A map showing the catchment (or wider) telemetry network	
C	A map showing all existing models and related studies	
D	A map showing forecast locations and requirements	
E	A list of telemetry sites	
F	A list of other hydrometry	
G	Summary of available sources of rainfall forecasts	
H	A list of structures included	
I	A list of structures excluded	
J	Other (please suggest)	

APPENDIX 2 – GLOSSARY OF FLOOD FORECASTING TERMS

Table A2.1. Glossary of scientific terms		
TERMS	**DEFINITIONS**	**NOTE**
Automatic calibration	The calibration of a mathematical model using automated optimisation methods in which some measure of the difference between gauged and simulated data is typically minimised.	General scientific usage. W5C – 013/4/TR quoting the NFWC
Base model	A calibrated and verified model.	W5C – 013/4/TR quoting the NFWC
Black box models	Rainfall runoff model where the relation between them is metric (fitted directly to data, with no representation of physical processes).	General scientific usage.
Calibration	The process of back calculating or estimating the values of conceptual or empirical parameters in the equations used within a model. The process is often carried out through trial and error comparisons of gauged and simulated values.	General scientific usage. Estuaries Report
Calibration envelope	The extremes of the calibration data set.	Defined in W5C-013/5/TR text
Conceptual hydrological model	A rainfall-runoff model that represents stores and transfers of water through notional storage volumes.	General scientific usage.
Continuous modelling	A flood forecasting practice based on continuously running flood forecasting models.	W5C – 013/4/TR quoting the NFWC
Design flood	A flood event corresponding to some prescribed criteria, usually a flood peak of specified return period.	
Discharge routing module	A forecasting module that uses a water budget form of the conservation of mass to calculate flow but not level at all computational points.	SEFFS
Distributed rainfall-runoff model	A rainfall runoff model in which the rainfall input and/or response parameters and functions are spatially variable.	
Dynamic data	The subset of the model dataset that embodies event specific or time-varying information.	
Empirical models	Models developed by fitting a mathematic function to the observed data using regression analysis or some other method of inference.	
Flood forecasting	The prediction of peak flows and levels and the times that they will occur.	W5C – 013/4/TR quoting the NFWC
Flood routing	Routing is a term given to calculation procedures for determining the modification of flood waves travelling in open-channels. Broadly there are two methods (i) hydrological routing (encompassing channel routing and reservoir routing), (ii) hydraulic routing (encompassing kinematic routing, diffusion analogy and hydrodynamic routing).	W5C – 013/4/TR quoting the NFWC
Flow to flow correlation	Correlations between flows at upstream and downstream sites used to predict downstream flows, with a rating equation used to predict levels at the forecast site. Multiple correlations may be used (i.e. based on two or more sites), and correlations may be specific to particular flow conditions.	
Hydrodynamic model	A 1-D, 2-D or 3-D computer solution to the governing equations expressing mass and momentum or energy conservation in a river or estuary. Only the 1-D solution is widely used for real time models.	
1-D hydrodynamic modelling	A modelling approach based on the Saint-Venant equations capable of predicting discharge and water level for a wide range of rivers, reservoirs, complex floodplains and narrow estuaries.	W5C – 013/4/TR quoting the NFWC
2-D hydrodynamic modelling	A modelling approach based on the shallow water wave equations capable of predicting flows and water surface elevations in two dimensions. The approach can cope with lateral variations in depth and velocity and is particularly useful in modelling wide estuaries and flows over side weirs.	W5C – 013/4/TR quoting the NFWC
Hydrological routing	Routing that encompasses channel routing and reservoir routing only (i.e. conservation of mass only: inflow - outflow = change in storage).	
Integrated model	Model that incorporates different types of modelling approaches to represent different parts of the catchment or system. For example a	

Table A2.1. Glossary of scientific terms		
TERMS	**DEFINITIONS**	**NOTE**
	rainfall runoff model combined with a routing model.	
Kinematic routing	Hydrological routing based on the kinematic wave equation in which the gravitational force driving the flow balances the frictional force resisting it.	
Lead time	The time by which the forecast of an incident precedes its occurrence (or non-occurrence).	Estuaries Report
Level to level correlation	Level-to-level correlation refers to expressions (usually linear functions in the form of tables, graphics or equations) for forecasting peak water levels at one site from peak water level at another (usually upstream) site. In some cases levels at two or more upstream sites are used to forecast level downstream.	Estuaries Report
Lumped rainfall-runoff model	A rainfall-runoff model in which a single rainfall value is used as the model input at each forecasting step (this implicitly assumes rainfall to be spatially uniform) and the parameters are effective, areally-averaged quantities.	Defined in W5C-013/5/TR text
Mathematical model	Representation of flows through physical systems by a set of theoretical or empirical equations supported by appropriate data. To practitioners, mathematical models are often synonymous with specific software packages.	Estuaries Report
Milestone	A point in a project, planned in advance, where it can be demonstrated that progress has been made, e.g. by having an interim report, project note, letter, working model file, data set or prototype software.	
Model verification	A confidence building process in modelling, whereby the calibrated model is further used to independently predict an independently gauged event meeting the same criteria as used in calibration.	Estuaries Report
Modelling Approach	Mathematical approach used to represent flow of water in physical systems, categorised according to the degree of complexity and detail as follows *Empirical models* *Black box models* *Conceptual models* *Hydrological Routing* *Kinematic routing* *Hydrodynamic routing.*	SEFFS Estuaries Report
Parameter updating	Updating procedure where the correction is applied to the model parameter(s) based on comparisons of forecast values and real-time data.	Defined in W5C-013/5/TR text
Post event audit or analysis	Review of flood forecast or flood warning performance following a flood incidence or a flood season to quantify the performance of the forecast and warning system.	
Routing model	A model that translates flows from the upstream to the downstream end of a river reach allowing for attenuation, floodplain effects, tributary inflows and so on.	
Semi-distributed rainfall-runoff model	A rainfall-runoff model in which the catchment is divided into a small number of homogeneous zones, or a distribution function of responses, that contribute to the flows in the main channel further downstream.	Defined in W5C-013/5/TR text
State updating	Updating procedure where the correction is applied to the model state, e.g. depth of water in a conceptual store.	Defined in W5C-013/5/TR text
Static data	The subset of the model dataset that embodies non event specific information, such as physical characteristics that do not change over time.	
Transfer function	A type of time series model in which the forecast flow depends on past flow and (lagged) rainfall.	Defined in W5C-013/5/TR text
Updating	A process by which simulated and observed time series at one or more gauging stations during the pre-forecast periods are compared in order to determine a correction to apply during the forecast period.	

Table A2.2. Glossary of flood forecasting & modelling platforms used within the Agency	
TERMS	**DEFINITIONS**
AFFMS	The Anglian Flood Forecasting Modelling System currently under development by the Danish Hydraulic Institute (DHI).
DODO	Douglas and Dobson Routing Model used in the Midlands Flood Forecasting System.
FFP	Flood Forecasting Platform: Southern Region's PC based system for running forecasting models.
MCRM	The Midlands Catchment Runoff Model used in the MFFS
MFFS	The current Midlands Flow Forecasting System. Sometimes called FFS2.
NFFS	National Flood Forecasting System.
RFFS	River Flood Forecasting System currently used by the Northeast Region, developed and marketed by CEH Wallingford.
RFFS-ISIS	A flood forecasting system currently used by the Northeast Region, developed by the association of HR Wallingford and CEH Wallingford.
SEFFS	Southern Enhanced Flood Forecasting System.
WRIP	Flood forecasting system for transfer function rainfall-runoff modelling.

Table A2.3. Glossary of software packages available for modelling/forecasting of fluvial floods	
TERMS	**DEFINITIONS**
Delft-FEWS	Delft Hydraulics' Flood Early Warning System.
DWOPER	A Hydrodynamic Model produced by the United States National Weather Service.
FloodWatch	A flood forecasting package developed and marketed by the Danish Hydraulic Institute (DHI).
FloodWorks	A flood forecasting package developed and marketed by Wallingford Software Ltd.
HYDRO-1D	A Hydrological and Hydrodynamic Modelling System developed and marketed by Mott MacDonald Ltd.
HYRAD	A weather radar processing, forecasting, calibration and display package developed and marketed by CEH Wallingford.
ISIS	A Hydrological and hydrodynamic Modelling System developed and marketed by the joint venture between Wallingford Software and Sir William Halcrow and Partners Ltd.
KW	Kinematic Wave model developed by CEH Wallingford. It uses attenuation and delay parameters to simulate kinematic effects instead of routing kinematic flood waves through survey cross-sections.
MIKE11	The Hydrological and Hydrodynamic Modelling System developed and marketed by the Danish Hydraulic Institute.
PDM	Probability Distributed Moisture Model. A rainfall-runoff model developed and marketed by CEH Wallingford.

Table A2.4. Other abbreviations	
Abbreviation	**Full title**
GMS	Generic Modelling Specification
NFFG	National Flood Forecasting Group
NFFMSS	National Flood Forecasting Modelling Systems Strategy
NFWC	National Flood Warning Centre
NFWMG	National Flood Warning Management Group
SFRMF	Strategic Flood Risk Mapping Framework

APPENDIX 3 – OUTLINE MODELLING SPECIFICATION FOR FLOOD FORECASTING

Revision History

Draft/ Date	Prepared by	Reviewed by	Notes
Draft A, undated	Rahman Khatibi, EA National Flood Warning Centre	Mike Vaughan, EA Southern Region Paul Wicks, Halcrow Marc Huband, WS Atkins	Aligned to NFFS tender specification.
Draft B, April 2002	Rahman Khatibi, EA National Flood Warning Centre Dan Cadman, EA Anglian Region		Aligned to NFFS tender specification.
Draft C / OMS December 2004	JBA Consulting Engineers and Scientists		Revised to align with Protocols for minimum standards in modelling. Stages revised following consultation to be more inclusive of modification of design models for forecasting, in addition to new model build. Renamed Outline Modelling Specification.

INTRODUCTION

Purpose and aims

This document describes a general specification, the Outline Modelling Specification (OMS), to be followed in the course of commissioning, adapting or improving a river model for the purposes of real time flood forecasting.

The purpose of the specification is to formalise modelling practice into a single consistent methodology and encourage a structured and auditable procedure to be followed during model development. The overarching aim is to ensure that all models developed for Agency business, whether for flood forecasting or otherwise, are fit for purpose, and that the model assumptions, limitations and outputs are properly understood and documented.

The OMS describes the activities and considerations required at each step in the development of a flood forecasting model, from project inception through to model delivery. It is generic in the sense that it is intended to cover a whole range of approaches that might be used to model fluvial floods, including empirical methods, rainfall-runoff models, transfer functions, channel routing and hydrodynamic modelling, or hybrid approaches of the above. It also specifies how river models constructed for the purpose of flood risk mapping, flood alleviation schemes and other studies should be adapted for use in real time.

The OMS has been prepared by several key staff within the flood forecasting business and should be considered as authoritative in its content. However it is intended that the specification will be updated and improved over time, based on the experience of its users. Feedback on the specification is welcomed.

Scope

The OMS is a technical specification only. It is independent of, and does not include, project management, costing or contractual terms.

All modelling is expected to comply with the OMS unless it is stated otherwise in the Terms of Reference (ToR) of the project. However, the following points should be noted:

- The OMS is applicable to modelling projects undertaken ‘in-house’ (by Agency staff) as well as those contracted out to consultants.
- The OMS should be assumed to provide the context for, and not supersede, any detailed specifications for any given modelling approach or technique.
- The OMS is intended to complement the existing Flood Risk Mapping (Section 105) Specification for the development of design models (to be used in flood risk or flood defence applications) and refers to that document.
- Where project specific requirements conflict with the OMS, they should always be considered to supersede any generic modelling considerations.

For some problems for which models are developed to solve, there is a Good Practice approach that sets a framework for the modelling activity and / or provides detailed guidance regarding the appropriateness of different modelling techniques. Examples include the Flood Forecasting and Warning Good Practice Baseline Review (Defra R&D Publication 131), Flood Forecasting – Real Time Monitoring (R&D Technical Report W5C-013/5/TR) and Guidelines for Forecasting Extreme Water Levels in Estuaries for Flood Warning (R&D Technical Report W5/010/1). Where relevant Good Practice is available it should be used in conjunction with the OMS as appropriate.

Organisation of the OMS

The OMS is organised around a five-stage division of established modelling practice, as outlined in Table 1. This is a widely accepted interpretation of 'the modelling process' (e.g. see HarmoniQuA, Protocols W5C-021) and has been tentatively adopted by the NFFG.

The five stages, which can be thought of as marking milestones in the lifecycle of the model, are:

STAGE 1. Inception

STAGE 2. Conceptualisation and configuration

STAGE 3. Review

STAGE 4. Calibration and validation

STAGE 5. Testing

Application of the tested model on an operational basis can be thought of as a sixth stage, but one that, in general, is unlikely to require significant input from 'the modeller'.

The modelling specification presented within this document is defined separately for each stage. In each case the OMS sets out the tasks, activities and considerations required, as summarised in Table 1. It should be noted that, for any particular project, these generic requirements may differ from those set out in the Terms of Reference (ToR). It is therefore important that the modeller and project manager confirm, at the outset of the project, what the modelling must deliver and what specific tasks need to be undertaken.

The OMS also specifies distinct outputs that must be demonstrated if milestones are to be achieved, including documentation and model outputs. Furthermore, progression to subsequent stages of the modelling procedure will depend upon formal Agency approval of milestone outputs, through Protocols for Minimum Standards in Modelling (R&D Technical Report W5C-021).

Table 1. Generic stages in modelling practice for flood forecasting models

Stage/ Milestone	Tasks	Details / aims	Output
1: Inception	- Identify available data - Review of existing models - Catchment characterisation - Schematisation	The model inception phase. Scoping of potential modelling approaches based upon forecasting requirements, data availability, previous studies and key aspects of the physical system. Leading to specification of modelling approach and preliminary model schematisation.	- Inception report - Technical programme - Preliminary schematisation
2: Conceptualisation and configuration	- Collation & quality assurance of data - Manipulation / process of data - Quantification of catchment processes - Initial model build	Detailed conceptualisation of the hydrologic and hydraulic behaviour of the physical system, discretisation into channel reaches or subcatchments as appropriate. Verification of input data and subsequent manipulation to evaluate model parameters. Progression to model build using proprietary software package or bespoke programming.	- Project data register - Model build log - Preliminary (or 'raw') model
3: Review	- Review of raw model - Sensitivity tests	Review to ensure model is parsimonious and that all model components are necessary, using sensitivity tests if appropriate. Revision of built model if required.	- Interim report - 'Parsimonious' model
4: Calibration and validation	- Calibration - Validation	Calibration and validation phases, where model parameters are optimised by referencing the model outputs to observed data.	- Calibration report - 'Validated' model
5: Testing	- Offline testing - Testing in emulated real time	The test controlling phase where the model is tested both offline, and within an emulated real time environment.	- Full modelling report -'Tested' model
6: Application	- Operation in forecasting environment - Maintenance	Application as a 'live application' in an operational flood forecasting environment Maintenance and of the model	- Functional forecasting model

Documentation

Documentation can be considered as a running theme within the OMS, and applies at all stages of modelling. Adequate documentation is absolutely vital if the final model is to be fully auditable, and can be considered as an essential output of each module. Documentation is to include recording of decisions made throughout the modelling process, as well as fully reporting the final model structure and performance of the model during calibration and testing. Documentation should be sufficiently comprehensive to facilitate any future maintenance, modification or improvement of the forecast model by specialist staff.

Model outputs

Specified model outputs vary from stage to stage, beginning with a preliminary schematisation at the Inception stage and progressing to a fully tested and validated parsimonious model by the fifth stage, Testing. However the detail of each model is dependent on the modelling approach applied and the OMS is prescriptive only in general terms.

Data

Data forms an important element in several of the stages of the modelling process. Collection, collation, verification and manipulation of data and information are all required. As it is difficult to compartmentalise these procedures, it is not intended that the OMS be overly rigid in this respect. For example, a data requirement or problem that had not been anticipated could require data collection quite late during the modelling process. However it is intended that the bulk of any data collection should be carried out in the initial stages of the project.

Applying the OMS

Whilst the role of the specification is to promote increased consistency in modelling practice, it is recognised that modelling projects may not always be implemented in a strictly linear fashion, as implied in Table 1, and that a degree of flexibility is often required. For example where the modelling builds on previous work only parts of the specification might be of relevance. Similarly where a simpler modelling approach is utilised. In others it may be difficult to differentiate where stages may need to be lumped together.

It is similarly acknowledged that the modelling procedure can be cyclical in nature, both between and within stages. For example, the conceptual understanding of the catchment may develop during the model build process. In such cases the aim of the OMS is not to impose a rigid solution, but to encourage proper justification of the decisions made or solutions implemented if a model develops ‘organically’.

Therefore within the specification each stage of the modelling procedure is treated as a self-contained ‘module’ having distinct inputs and outputs. This modular system allows a degree of flexibility to be incorporated into modelling practice, whilst keeping that tasks and activities within a consistent framework. For instance it allows the specification for modules to be amended as necessary for any given project, or for a project to commence any stage (if building upon previous work, for example). The modular system also allows for the division of a modelling project between different modellers and facilitates model revision, if necessary, at a later date.

Unless specified in the terms of reference deviation from the modelling procedure outlined above should only be made in prior agreement with Agency staff and, as described earlier, progression to subsequent stages of the modelling procedure will depend upon formal Agency approval of milestone outputs, through the use of Modelling Protocols.

STAGE 1: PROJECT INCEPTION

Overview

Stage 1 is the inception phase of the modelling project. Here the outline problem stated in the Terms of Reference is developed into a 'preliminary model' reflecting the best knowledge of the system, the amount and quality of available data and the type of solution required. Subsequent stages of the modelling project go on to review, refine and test this model.

As it underpins the whole modelling process, the Project Inception can perhaps be thought of as being the most critical stage within a modelling project. Mistakes made here may be difficult to rectify later. Project Inception can therefore be a very intensive phase of the modelling process. It should consider and plan for the following tasks:

- Scoping
- Selecting the modelling approach
- Schematisation
- Data collation
- Model building

These elements are interconnected, that is, they cannot be conducted completely independently of each other. For instance schematisation depends heavily on the modelling approach used, whilst both schematisation and abstracted data must be used in tandem towards building a preliminary model of the system. Many of the specifications presented under these headings are therefore generic (to Project Inception) in nature.

The whole process of Project Inception can be considered an iterative one, with the stages repeated or revised until a satisfactory preliminary model is achieved. There are strong links with Stage 3 (Review) and Stage 4 (Calibration and Validation). The required deliverables of Project Inception can be summarised as:

- A preliminary outline of how the model is to be built or modified (i.e. preliminary schematisation)
- A report detailing the consideration of alternative approaches and the selected modelling solution
- The recommended technical programme of work.

<u>Scoping</u>

The focus of the Scoping element of Stage 1 is to identify appropriate modelling options given the conditions of accuracy, reliability and so on prescribed in the Terms of Reference. Scoping therefore considers all other four elements (model choice, schematisation, data collation and model building).

Selection of modelling solutions

Model selection must take into account a number of considerations including technical issues, cost-benefits and 'risk'. Naturally, more sophisticated modelling solutions will be supported where the catchment or the technical nature of the problem is complex and sufficient data can be made available, whereas a simple solution may be more justifiable and robust in other cases (Figure 1).

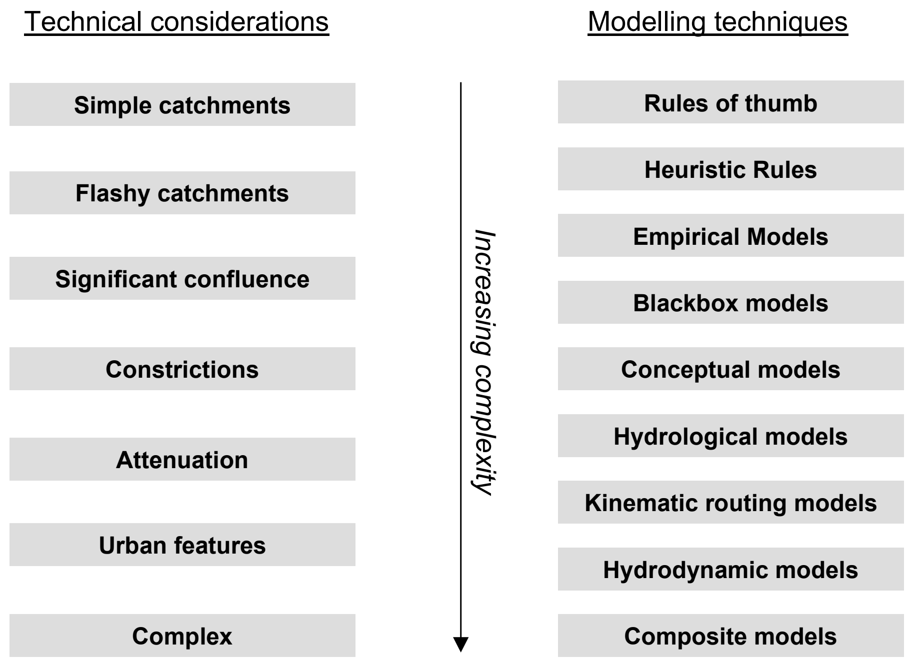

Figure 1. Technical considerations and possible solutions

The process of model selection will be facilitated by referring to appropriate guidance on the subject. Recent documentation that is relevant includes the following:

- Fluvial only systems: Tilford et al. 2003. Flood Forecasting – Real Time Modelling. EA R&D Technical Report W5C-013/TR.

- Estuarine systems: Guidelines for the Use of Appropriate Methods for Forecasting Extreme Water Levels in Estuaries for Incorporation into Flood Warning Systems

- In addition the Guide to Best Practice in Coastal Flood Forecasting (Defra / EA) gives some guidance on coastal flooding.

Naturally, more than one 'modelling approach' is often feasible, and in such cases it is especially important to take account of risks and costs associated with each candidate modelling solution. In particular it is important to determine:

- the benefits or avoided costs if a forecasting solution is implemented, and

- the risks associated with a proposed solution.

Some consideration must also be given to how the suitability of the forecasting approach could be monitored.

Schematisation

Schematisation is the process of transforming the physical system and its hydrological/hydraulic processes into a sequence of interconnected modular units, the aim being to provide a succinct description of the catchment. The Schematisation facilitates the process of data abstraction, as its modular framework allows comprehensive and rapid collation of knowledge on the catchment from a variety of sources.

The schematisation also provides a basis for familiarisation of Agency staff with the system, which allows them to better ensure that the Contractor has examined the physical catchment system prior to any consideration of modelling options.

Schematisation should also identify an appropriate level of detail for the selected modelling solution.

Existing models may provide a convenient starting point, and there are a number of ways in which these can be used, such as:

- direct migration of an existing model to the forecasting environment
- providing guidance in schematisation of an entirely new model
- extension (in terms of geographical extent) or simplification
- incorporation or removal structures, control logic and river cross sections.

A key aim is that the proposed schematic should deliver a model capable of predicting the hydrological/hydraulic behaviour of the catchment to the required accuracy, timeliness and reliability as specified in the Terms of Reference. The Review stage (Stage 3) and Calibration and Validation stage (Stage 4) should then demonstrate that this has been achieved.

Data collation

It is impossible to specify an all-encompassing list of data requirements for modelling. This is a widely recognised problem, which is simply due to there being different data requirements for different types of model and for different stages in the modelling process.

However Table 2 gives an indication of the range of information that may be required to give an adequate representation of the catchment in any particular case. This list is not exhaustive and there are other “data” necessary to achieve the desired result, e.g. mathematical parameters such as time and space step or other weighting factors used by the model solution algorithms.

Not all the data collated at Project Inception stage will necessarily be used in the model build. Some of the data will be used during later stages, e.g. calibration and validation.

However data abstraction is not necessarily limited to project inception and may be required at any stage in the modelling project.

Table 2. Generic input data types

Data type	Description	Example	Sources
Static data	Any boundary or initial values that remain unchanged during the whole modelling / forecasting period.	Model extents, "sweetening" flows	Specification, calibration
Dynamic data	Time series that are updated at set time intervals.	Rainfall data, Annual maximum flow or level data.	Digital /paper archives, library searches, photographs etc.
System data	Typically a set of physically quantifiable values that describe some catchment attributes. This also includes any calibration parameters that have a physical interpretation.	Survey data, weir coefficients, roughness parameters.	Maps, GIS files, asset databases and records, existing surveys
Control data	Physical values that may be set manually or automatically in interaction with the hydraulic behaviour of the system	Gate openings, reservoir operation	Operating authority records
Output data	Values of the dependent properties determined through modelling/forecasting,	Depth, discharge, velocity.	Model

The process of collating data can be thought of as consisting of a number of stages:

- Sourcing data
- Collection of data
- Verification of data
- Manipulation of data into required formats

Sources of the various data types are indicated in Table 2. System data is typically obtained from maps, GIS files, asset databases and records, and existing surveys (may require interpolation or extrapolation). Time series or sample data can usually be sourced from digital or paper-based archives, or, for unusual data such as notable extremes, from library searches, bridge markings, photographs etc. Much of the data will be available from Agency records or archives, but in many cases data will need to be sourced from 'external' organisations such as Ordnance Survey, British Geological Survey, British Soil Survey, Centre for Ecology and Hydrology, Meteorological Office, Water Companies, Internal Drainage Boards and other academic institutions.

Existing models, if available, will also be a very useful source of data, and should be utilised where possible, provided the data can be suitable verified or audited.

It will be often necessary to initiate a programme of field data collection, especially where the required modelling approach is complex. This may include new/additional topographic or structural surveys, hydrometric measurements, and geological or other investigations. For instance it may be necessary to install additional hydrometric or telemetry equipment.

Verification of data is a critical element in data abstraction and should always be undertaken as fully as possible.

Data will often be provided in a 'raw' format that must be manipulated into a usable form. Example manipulations might include calculation of the flows from level records and a rating, contouring of rainfall data, flow naturalisation, processing of ultrasonic gauge data, data substitution or infilling.

Where possible any data manipulation undertaken should follow the relevant best practice / guidelines or specified in-house procedures where available. For example flow naturalisation would be undertaken in accordance with the Agency Good Practice for Naturalisation of River Flows.

Preliminary schematisation

The preliminary schematisation is the culmination of the Inception stage, and should be an intuitively reasonable representation of the physical system. However, whilst it reflects the best design information available, the preliminary schematisation will not necessarily resolve every detail of the catchment / river or modelling solution, rather it should set out the overall approach.

Specification

Selection of a modelling solution

The modeller shall review the modelling problems in the catchment and identify a range of modelling options. At this stage, the review should concentrate on general issues and solutions, and need not detail the schematisation of individual catchments, unless by way of an illustrative example.

Having reviewed the options, the modeller shall reconcile the data requirements of the selected modelling solution with the available data and if necessary initiate a programme of data collection subject to Agency approval.

Schematisation

The Contractor shall outline the hydrological/hydraulic behaviour of the catchment and demonstrate that the proposed schematic is capable of predicting the behaviour - this activity is the core of Stage 1. To achieve this, the Contractor shall review the accuracy, timeliness and reliability; range of recording (with associated accuracy, timeliness and reliability), period of record (including missing data), geographical coverage, timestep and telemetry links and archive source for each relevant hydrometric site.

Review of existing models

The Agency shall supply details of existing models relevant to the forecasting requirement. The Contractor shall review the purpose, suitability and extents of existing models and propose any necessary enhancements or revisions. Alternatively, a new schematic shall be proposed if the existing models are found to be unsuitable for the forecasting application.

Site Visits

Schematisation shall allow for site visits, meetings and/or interviews, so that the Contractor is fully familiar with all key aspects of the catchment and associated measuring sensors.

Channel Network representation

For those modelling approaches with an explicit channel network representation, the Contractor shall review the coverage and spatial resolution, date accuracy and quality of channel survey data. This shall include the coverage and availability for use of non-Agency surveys, such as surveys associated with developments or other studies.

The schematisation shall describe all aspects of the hydrological behaviour of the catchment that are significant. This includes climate, the natural and manmade physical features of the catchment, and the means of measuring input variables to an appropriate level of detail to impart an understanding. It shall also include any relevant unusual behaviour (for example the tendency of early season floods to be unusual due to drainage blockages etc) and its salient risks (for example particular vulnerability to blockage of a particular bridge, failure of a transfer scheme etc. Any documents that have been used to support the review, or provide information to it, shall be referenced.

Rainfall-runoff modelling

The catchment shall be broken down into a collection of linked subcatchments, as necessary. Subcatchment models shall represent the processes of rainfall–runoff (including the interactions between climate, soil, vegetation and groundwater) at an appropriate scale. Each subcatchment shall be as internally homogeneous as can achieved within the chosen modelling approach. Further subcatchments shall only be created where the catchment response is not likely to be homogeneous, or where forced by model structure or input data availability.

River channels

River channels shall be represented explicitly if they, or the features within them, exert significant control over the hydraulic response of the catchment at the timestep required. If an explicit river channel model is used, it shall represent the routing and in-channel processes (including where necessary the interactions with climate, vegetation and groundwater) at an appropriate scale.

Abstractions and Discharges

Abstractions and discharges can be lumped together or represented individually. The representation of abstractions and discharges shall be determined by the significance of their impact on the water level as defined in the Agency's Good Practice for Flow Naturalisation.

Structures

For modelling techniques explicitly incorporating the channel network, structures shall be explicitly included where they exert a significant control on the hydraulic behaviour of the channel.

Data review

The Contractor shall perform any data collation, collection, and manipulations appropriate to underpin the schematisation.

Preliminary Schematisation

Where physical properties or features are explicitly represented in the model schematisation, the numerical representations and reference names or codes shall be accurate and consistent with the Agency's definitive databases.

Outputs

Stage 1 should deliver an Inception Report describing:

- the proposed general modelling approach,
- a schematic outline of the model to be delivered,
- a discussion of alternative approaches and why they are not considered suitable,
- a review of data sources and possible constraints,

It should also deliver documentation of the recommended technical programme of work.

Inception Report

The report shall include a description of existing models and the selection of a new modelling solution. Any breaking down of the model into sub-models shall be specified. The unusual or difficult modelling problems that are anticipated shall be identified and the options for representing these within the chosen model scheme described. This description only need to treat the problems generically rather than specific to the location.

The output of Stage 1 shall assess qualitatively and quantitatively the accuracy, timeliness and reliability of currently used techniques, using any measures stipulated in the guidelines. The description shall be illustrated using maps to highlight spatial distributions, graphs highlighting temporal changes and schematics, diagrams etc. as necessary. For a full description of the catchment, relevant maps may be included.

The Inception Report shall also state the assessment of the performance of existing models and broadly identify main sources of uncertainty and how these can be represented. The report shall identify the data requirements of the selected modelling solution, including natural components of the hydrological cycle and artificial influences upon it.

The report shall identify data requirements and the sources available to meet these requirements. Where existing data is to be used, the source of the data and the quality assurance reviews and checks shall be reported. Examples of data collection may include new or improved hydrometric measurement, or topographic surveys (including infilling of existing survey, additional river sections, structures, bank top levels and floodplains).

The report shall indicate whether data availability is likely to be a constraint upon the implementation of the selected modelling solution in the subsequent stages. The Contractor shall review alternative data sources where the preferred source for any data is not present. The degradation in the performance criteria shall be indicated.

The report shall state the accuracy and reliability of the selected modelling solution. These performance criteria shall take due regard of the guidelines produced by the Agency, British or International Standards, WMO Guidelines, other Agency Good Practice and the Contractor's knowledge of practices elsewhere. Examples include the Agency Good Practice for Naturalisation of River Flows, Quality Assurance in Computational River Modelling, October 1993 by HR Wallingford, and the Guidelines for Acceptance of ISIS and Other Hydrodynamic Module Datasets for Flood Forecasting (2004).

The selected modelling solution shall be the most appropriate to solve the problem and raise the Agency performance to the required standard, making suitable allowance for the data available. This solution is inclusive of risks associated with the selected modelling solution. The alternative options shall be documented in outline, with justification for why they are not the best approach.

Recommended work programme

The specification of the programme of work shall include a list of reference documents to be reviewed. Those products of the searches that are not thought to be worth pursuing shall also be listed and justification for their omission from the programme given.

The specification shall also identify any individuals with whom it shall be necessary to meet or interview, and the data collection, collation and manipulation required to reviewing the preliminary model. These shall be detailed in a programme of site visits.

STAGE 2: CONCEPTUALISATION AND CONFIGURATION

Overview

Stage 2 is the model conceptualisation and configuration stage. This follows on directly from Project Inception. If the inception stage is seen as a detailed proposal for the modelling work, then Stage 2 is where the actual model development work begins. This stage includes 'model build', where a new model is to be produced. However, it is not necessarily limited to model build because there will be many cases where the task is to modify or simplify an existing model.

Conceptualisation

This stage of the Outline Modelling Specification has been named Conceptualisation and Configuration because it may start from a position where there is no existing modelling, in which case the first step is to conceptualise the system in detail, i.e. to decide which mathematical or software functions should be used to represent each physical feature.

Conceptualisation requires some quantification of catchment processes (that should have been identified at the Inception stage, but not necessarily quantified); for example, extents of tidal influence, backwater or floodplain flows. The detailed conceptualisation of the hydrological and hydraulic behaviour of the physical system would also include discretisation into channel reaches or subcatchments.

The conceptualisation will include initial model build or modification using proprietary software packages or bespoke programming.

Configuration

Following conceptualisation, there will always be a need to configure a model for use, which in this context means preparing the model data, boundaries and initial conditions for review and then calibration and validation. This 'configuration' task is likely to include the collation and quality assurance of data, manipulation and pre-processing of the data and derivation of first estimates of model parameters.

Configuration also includes the setting up of model input data files and establishing a data register, model build log and record of model runs carried out.

Specification

Channel network representation

Recommendations for the model structure shall include any partition of the model into submodels, the detailed breakdown of the channel network and catchment into subcatchments and channel reaches, the selected modelling solution for each subcatchment and channel reach and the representation of catchment or channel features. Features include natural hydrological or hydraulic features and artificial features such as in-channel or off-line structures, abstractions and consented discharges.

The schematic shall include the breakdown of the catchment and river network into subcatchments and channel reaches that represent sensible hydrological and hydraulic units. The expected behaviour of the subcatchments and components of the channel network shall be described. The breakdown into subcatchments shall reflect the heterogeneity of significant hydrologic catchment characteristics (e.g. area, soil type and land use). The schematisation of hydraulic units will mirror hydraulic behaviour of the channel e.g. the presence or absence of flood plains, backwater effects etc.

The breakdown into subcatchments and channel reaches shall also take into account the location and effects of manmade influences such as abstractions, discharges, structures and pumps upon catchment and river behaviour. The significance of each manmade influence shall be estimated and a judgement made on whether it requires implicit inclusion in the model. The task of schematisation shall pay due regard to representing each natural processes or manmade influences by measurements and operating rules. This shall be done for both the quantity and quality of system data and the time variant input data.

Rainfall-runoff modelling

Wherever possible, each subcatchment shall be represented with a single representation and parameter set. The use of duplicate representations or parameter sets to allow the model to accommodate complexities in catchment behaviour, for example the different runoff responses of aquifer and non-aquifer, shall be justified, documented and agreed prior to implementation.

If several rainfall-runoff subcatchments are to be linked into one model, they shall be linked by a channel network, or nested. (Nested rainfall-runoff models effectively represent channels implicitly in the same way that lengths of channel headwaters are always implicitly represented in rainfall-runoff subcatchments.)

Pumped catchments are a special case of subcatchment where, as well as generating runoff from the pumped area, the model shall:-

- Account for the truncation of the outflow hydrograph from the pumped area at a discharge equal to the maximum capacity of the pumps.
- Account for the storage of water within the pumped area during periods when runoff is greater than the maximum pump rate.

River channels

The internal structure of the river channel network model shall reflect the boundary conditions and the hydraulic behaviour of the channel – i.e. the location of output data nodes, input data nodes, structures, changes in channel geometry and floodplain. The chosen solution scheme shall be appropriate to the hydraulic conditions of the reach represented at the chosen model timestep.

The upstream boundary of the explicit channel representation shall be determined by the most upstream requirement for a channel routing – generally the influence of a control on flow that cannot be satisfactorily incorporated by the subcatchment model. Where backwater effects are important, the downstream boundary of the model will be a site for which a full range Q-h relationship (where h is the upstream head) is known, or a location for which water level immediately downstream of the downstream boundary can be modelled. Throughout the channel network, significant changes in cross-section geometry shall be represented by separate flow panels.

If a 1-D hydrodynamic model representation is used, river channels shall be represented by the centreline (thalweg) of the river. The National Grid Reference co-ordinates used shall reflect this and the Agency's chainage system shall be used in representations of channel geometry. The minimum use of surveyed channel cross sections shall be at, immediately upstream and immediately downstream of nodes where water level is required output, and at any sudden changes in channel geometry (in terms of channel width or depth).

Floodplains shall be represented as a river or as storage as appropriate. Floodplains modelled as extensions of the river cross-section shall be represented by separate flow panels. Any ditches running parallel to the main watercourse in the floodplain with an embankment between them and conveying a significant amount of flow shall be modelled as a separate channel with appropriate connection to the main river. The Contractor shall justify and agree any use of other mechanisms (e.g. flood plain cells, linked storage areas) in advance of modelling. For perched rivers with embankments higher than the floodplain, the channel cross-section must be curtailed within the highest bank levels unless agreed otherwise.

Seepage from channel beds or embanked sections of channel shall be explicitly represented if it is a significant feature of the catchment and the problem. If the model cannot be linked explicitly to a groundwater or soil moisture store, seepage shall be represented either as an outflow/inflow time series (abstractions or discharges) or as a structure. An abstraction or discharge shall be preferred where such a time series can be defined. A structure shall be preferred where the rate of seepage is controlled by the head difference between the water level in the main channel and that in the surrounding medium.

Abstractions and Discharges

Abstractions and discharges that are represented explicitly shall interact with the appropriate model store. Surface water abstractions shall be represented as outflows from the river network. Groundwater abstractions shall be represented as outflows from the groundwater store of the catchment model. Control rules imposed by the model shall reflect either the explicit control rules by which the abstraction or discharge is operated or implicit operational practice.

Structures

Structures may vary from bridges, sluices, off-line storage reservoirs, weirs, dams and siphons. Where they are represented explicitly, the model shall reflect their hydraulic behaviour; for example, bridges shall be modelled as bridge units, loss units, culverts or as orifices.

At structures, both the river and the structure shall be represented correctly in the model. Therefore, structure dimensions and (where local scour and deposition effects are not significant) river sections upstream and downstream of the structure at locations shall be used at explicitly represented structures.

When viewed in long section using standard software, structures are to be located correctly and the river lengths are to be correct.

Data collation

The task of abstracting data shall include the identification of the data required for the model, including any reuse of existing models or derived data. Unless otherwise instructed, it shall be the responsibility of the Contractor to identify, locate and collate all relevant information and select from the data provided those that are necessary for the project. Whilst Agency staff may be able to give guidance for many data sources, Agency staff time shall not be used to collate the data itself.

The Contractor shall review and document the availability of reference material that may inform any stage of a modelling project. This shall include key-word and other searches on the world-wide web, searches through the Agency, CEH, British Geological Survey, British Soil Survey, Meteorological Office and Contractors own libraries, investigation of locally stored information and other material as appropriate.

Field data collection

If necessary the need for additional collection of field data shall be identified. The Contractor shall perform any field data collection identified. This shall be in accordance with the access rights agreed with the Agency and external holders of such rights. Data collection shall not be performed in such a way as to prejudice future Agency relationships or ongoing work at the site.

Data collection shall be performed in accordance relevant Health and Safety legislation. Generic risk assessments shall be made for all activities. The Agency's site risk assessments shall be reviewed prior to any site visits. The Contractor shall then make their own site risk assessments for all sites visited upon the first visit to the site. The use of the Agency's generic and site risk assessments does not remove the Contractor responsibility for their own risk assessments. The Contractor's proposed activities and relevant risk assessments shall be presented to the Agency's staff upon request for audit. The Contractor shall inform the Agency project manager and the Agency staff responsible for the site of any site visits, specifying what activities are to be undertaken, in advance of any site visits.

Prior to any visits the Contractor shall be responsible for checking with the Agency staff responsible for the site whether any significant changes have been made at the site since the Contractor risk assessment was created.

Data manipulations

The Contractor shall define the need for preparatory data manipulations and state the standards that are to be worked to.

Any standards proposed shall take due regard of British or International Standards, WMO Guidelines, Agency Good Practice and the Contractor's knowledge of practices elsewhere.

Outputs

Preliminary Model

Where physical properties or features are explicitly represented in the model schematisation, the numerical representations and reference names or codes shall be accurate and consistent with the Agency's definitive databases.

The National Grid References of location within the model shall be to the nearest 10 metres.

The default values of the parameters shall be consistent and appropriate to this stage.

STAGE 3: REVIEW

Overview

The Preliminary Model, as the output of Stage 2, is reviewed in Stage 3 by taking a holistic view of the objectives of the modelling project, the data available, the selected modelling solution, and the prescribed performance criteria in terms of accuracy, timeliness and reliability.

The aim of the review process is to evaluate the success of the initial modelling scheme, to determine if the level of detail is appropriate, and whether the end solution is of adequate resolution. That is, the Review is essentially a decision-making exercise in which the Preliminary model is developed into a more robust representation of the system. The report and Preliminary Model developed during Stage 2 form the basis for the review, the outputs being a 'parsimonious model' and accompanying documentation.

The parsimonious model should be as simple and robust as possible while fulfilling the requirements of the project brief. It should be 'sufficient', in the sense that it captures all available useful information about the physical system to forecast flows or levels, but no more than is needed. It should therefore be no more complex than can be supported by available and relevant data (this is of particular importance in rainfall-runoff and transfer function modelling where parameters controlling the response have to estimated by inference rather than observation).

The tasks involved in Stage 3 can therefore be grouped into three main activities:

- Review of the Preliminary Model
- Recording of decisions
- Developing a parsimonious model prior to final calibration and validation.

These will generally be implemented iteratively, until a satisfactory parsimonious model is developed.

<u>Review of the preliminary model</u>

Figure 2 is a schematic of the tasks required for model review.

The key theme in the review is to develop the preliminary model into the parsimonious model as an efficient and robust representation of the modelling problem. The main elements of the review process therefore include:

- The establishment of the significance, or lack of it, of any unit contributing to the reproduction of the system in the model
- The risk of removing a particular component from the model
- Obtaining an insight into the model through an appropriate representation of the system details and hydrological and hydraulic behaviours

- Reviewing the resolution of the selected modelling solution

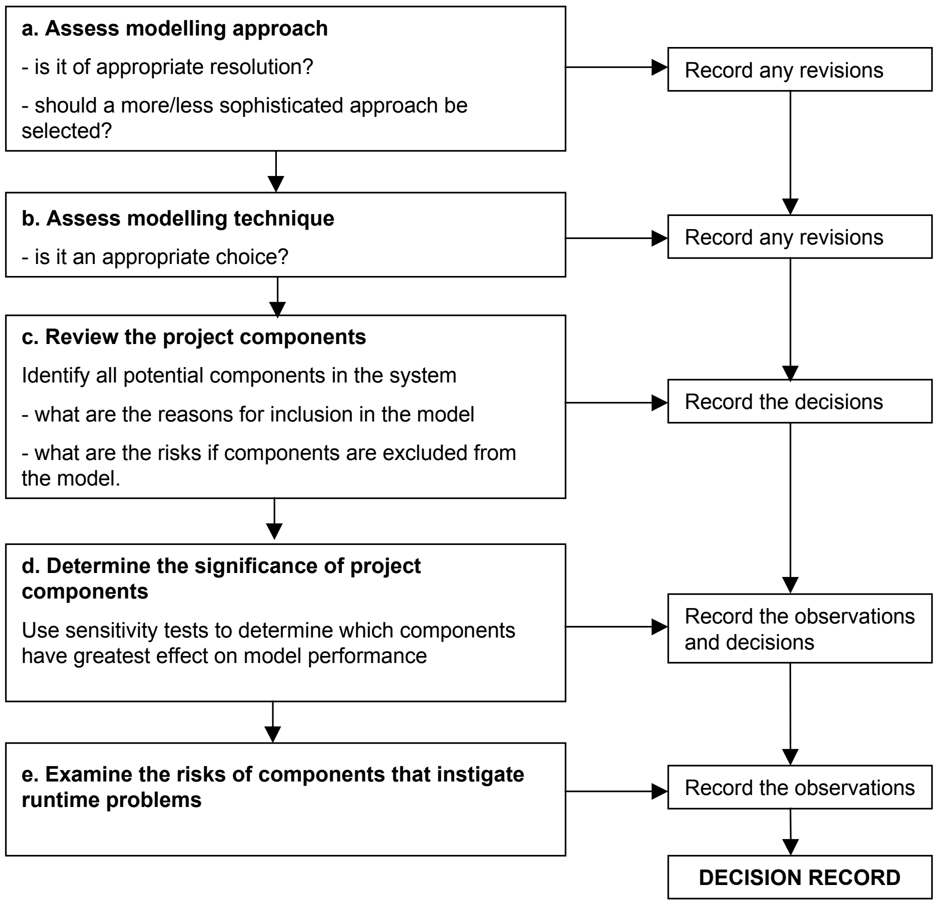

Figure 2. Elements in the review process

<u>Recording of decisions</u>

Formal recording of the decisions of the review process is vital for the purposes of model audit, and will form the basis of any documentation of the modelling procedure.

The recording outputs from each of the stages in the review process are shown on Figure 2. These are integrated to form the 'decision record'. The 'decision record' should therefore be a formal document that summaries the modelling approach, components of the model, key technical issues and so on.

Specification

<u>Review of the Preliminary Model</u>

The Contractor shall review the spatial and temporal coverage of the measurement network and consider expected errors and surrogate variables that could be used in the place of measurements.

Sensitivity tests shall be carried out to determine the impacts of different parameters and input variables and to prioritise the processes and interactions for inclusion in the model. Also, test runs shall be performed to determine which interactions exert sufficient influence to warrant explicit inclusion in the model. This prioritisation may in some cases be based upon expert judgement, but in others will require supporting quantitative analysis. For some interactions, it may be more appropriate to use the model itself to examine significance.

The review shall describe, and quantify where necessary, the significance of interactions between the various units/processes and indicate the relative importance of the catchment processes. Interactions or processes that have been excluded from the model as insignificant shall be listed and justified.

The review shall also pay due regard to the locations of points on the river network where the model output is required.

The review shall include site visits, meetings and/or interviews as and when necessary. The key here is to confirm the correspondence or omission between the components of the model and the real system.

The meetings with staff will present the gained insight of the catchment through the raw model to these staff so as to have a framework for discussion and to share knowledge amongst staff. The staff to be consulted and the mechanism for providing feedback on study findings to those interviewed shall be agreed with the project manager prior to the consultation. As a guide, Agency representatives to be consulted could include:

- Hydrologists (for surface water catchment and channel behaviour).
- Hydrogeologists (for the geology and aquifer behaviour).
- Flood Defence Operations staff (for structures, pumps, channel behaviour and some measurements).
- Flood Warning & flood forecasting staff (for details of flood warning and forecasting arrangements in the catchment).
- Flood Defence Improvements staff (for details of previous modelling and engineering projects in the catchment).
- Licensing or consents staff (for abstractions, impoundments or discharges).
- Hydrometric Staff (for measuring detail and behaviour of some structures).
- Modellers or other technical specialists by whom previous reports have been done (including external consultants).

The Contractor shall review data availability for the development of the preliminary model to the parsimonious model, check the quality of existing data and define a programme of data collection, collation, manipulation and verification.

The Contractor shall advise the Agency immediately if data collection is required to support the further a model development, or if the modelling should be deferred to allow for data collection/ monitoring.

The Contractor shall immediately, formally and explicitly recommend discontinuing or reviewing the modelling project should, in their expert opinion, a model no longer be the best or a justifiable approach.

Recording of decisions

The decision record shall specify the methods used for data collection, collation, verification, storage and manipulation for each category of data.

It shall also outline a fallback methodology for resolving any shortfall within the entire data should the Contractor discover unacceptable errors at any stage of the modelling procedure, for example, identifying data that can be substituted for the ideal source where this is not available.

The decision record shall also detail any key technical risks that the parsimonious model may not solve at this stage. These can be due to, say, difficulties in representing the catchment or inadequacies in the data associated with each sub-model, sub-catchment or channel reach, each of which may be revealed during the calibration and verification stage.

Any inconsistencies between the parsimonious model and expected behaviours shall be highlighted and justified. Uncertainties in the modelling, or conflicting evidence that cannot be reconciled within the model and the system, shall be thoroughly documented.

Parsimonious model development

The parsimonious model shall be a robust and physically reasonable trade-off between the catchment processes and the simplification required to facilitate understanding and the physical system.

The parsimonious model shall help interpretation or quantification of the underlying interactions in the catchment to the level of detail required by the performance criteria.

Outputs

The Contractor shall corroborate an understanding of the system with the understanding of key Agency staff and/or external individuals and these will be reflected in the deliverables of Stage 3. It is recognised that some of the deliverables may reflect relevant considerations for the subsequent stage of the modelling procedure. The Contractor shall flag any such information and agree an approach with the Agency.

The deliverables are:

- Parsimonious model
- Interim report
- Decision record

The parsimonious model

The parsimonious model should be delivered along with associated data files to the requirements agreed between the consultant and project manager. Formal documentation of model data files is not required at this stage unless specifically requested.

The parsimonious model shall be used to develop a view of applications towards current, future or other scenario conditions.

Any potential difference between these and the conditions prevailing during the calibration, verification and warm-up periods shall be envisaged and outlined in the report. The consultant shall identify, for reference during calibration (Stage 4), any subcatchment or channel reach where modelling problems are identified in the parsimonious model. As far as possible, the solutions given for these problems shall be in line with the generic solutions identified in the Inception report (and need not be detailed individually where they are). Detail shall be given of any approaches that have not been previously covered.

Interim report

The Report should define the further developments compared with the Stage 2 output, as well as the requirements towards and planning of model calibration and verification.

This shall include calibration priorities (e.g. low or high flow range), the strategy to ensure adequate representation of this flow range, timesteps, calibration, verification and state warm-up periods, approach to parameter uncertainty estimation and whether isolated events or continuous (full range) data shall be used for the calibration. For forecasting applications, the calibration approach to updating and/or error prediction techniques shall also be reviewed.

The Interim report shall build upon the Inception Report and specify, in detail, the further developments from the preliminary to the raw model and the approach to collating, collecting, verifying and manipulating the modelling data into a modelling database. It shall also indicate the likely run time of the model.

Documentation

The documentation shall identify any potential problems identified in the model or any unusual approach. Likewise, it shall identify locations where gaps in measuring networks could be expected to limit or significantly impact upon model performance.

The documentation shall define the use of model annotation, navigation and viewing facilities for the model.

STAGE 4: CALIBRATION AND VALIDATION

Overview

In this stage of the modelling process the parsimonious model specified in Stage 3 is calibrated using selected data from observed flooding. Its performance against available test data is considered (tested against historic flooding information as this is not a test of real-time performance).

Calibration and verification procedures are used to ensure that the model is adequately simulating the river system it is intended to represent within the scope of the study. It is therefore inevitable that some changes in the model may have to be made as understanding of the catchment improves at this stage.

During calibration, the values of unknown model parameters are adjusted until a satisfactory model output is achieved. Model parameters that are unknown at this stage may include geometric, hydrometric and empirical parameters. This process is often based on assumptions about the conditions affecting the historic flows, levels, and flood extents, using skill, care and expert judgement.

Specification

Calibration and validation issues

Calibration should be attempted only when a satisfactory parsimonious model has been achieved. For multi-component models, this means that calibration should not be attempted for any individual component prior to finalising the configuration of any other components that may be dependent on it.

The calibration process should not compromise the configuration of the parsimonious model. Any changes that are made to the parsimonious model as a result of calibration shall be fully justified and documented.

Following calibration the model should be validated with reference to at least one independent event. Any assumptions of made during calibration and validation, including expert judgements are to be fully recorded.

Calibration Data

Regardless of whether continuous or event data are used, the calibration data shall encompass the full range of flows of interest, plus the transition across the range of flows (winter to summer, summer to winter, spates etc). They should also seek to encompass the operation of important influences - such as artificial influences or the effect of floodplain flow in at least one event. Where available and appropriate, mapped flood extents shall also be used in the calibration, at least for qualitative comparison.

The selection of data for warm-up of model stores, calibration and validation shall balance the availability of good quality data, data handling and the use of a representative period of data. The modeller shall justify the selection of warm-up, calibration and validation periods. In particular the modeller shall advise where the selection of events or periods has used a subset of available data either due to the use of more data offering diminishing returns to the success of the calibration or to one or more of the above constraints. In particular any limitations caused by the range or regime of flows experienced during the calibration period for modelling the catchment response required by the problem shall be defined, and indicative accuracy of the outputs shall be given for the proposed model given the available data.

The periods used for calibration and validation should be as long as possible within the constraints of the other factors. For a model calibrated on isolated events, not less than five events shall be used to calibrate a hydrological model and three events to calibrate the hydraulic model. All events used for calibration shall be of different magnitudes so as to provide separate tests of model behaviour over a range of flows. An independent flood or spate event shall be defined by the criteria used in the FEH report.

The definition of the data to be used includes the parameters to be calibrated to, the time periods used for warm-up, calibration and verification, and the input and output data at each model boundary for each of these periods. The error in measuring or estimating input data shall be quantified to an appropriate level of precision and accuracy.

Calibration Methods

Calibration includes any of (i) automatic parameter optimisation to a single parameter set, (ii) Monte-Carlo multiple parameter sets, or (iii) manual simulation to a single or a few parameter-set. If appropriate, a description will be provided to (i) the optimisation objective function and priorities for the calibration and (ii) the approach to calibrating to different conditions within the flow ranges or calibration period.

Automatic calibration facilities shall not be used to the exclusion of using expert judgement to choose, interpret and finalise the appropriate parameter set. If automatic parameter optimisation is to be used, the independence of the parameters is to be indicated and the likely effect upon the optimisation defined. If manual simulations are to be used to the exclusion of automatic calibration, the consultant shall indicate the steps to be taken to achieve optimal calibration.

Calibration shall be conducted moving from upstream to downstream (where the selected modelling technique is not capable of modelling backwater effect). Similarly, calibration of the floodplain shall not precede calibration of the river channel.

The description of how subcatchments, channel reaches and features will be represented and calibrated shall be appropriate to their importance and consistent with their proposed representation in the model. For example, minor abstractions and discharges may be lumped, and described in lumped terms. The representation and calibration approach shall be outlined for every structure and major abstraction or discharge to be included in the model. All subcatchments, channel reaches or features at the appropriate scale shall be listed and justification given for those proposed not to be explicitly represented in the model.

The Contractor shall consult with operational staff as appropriate to ensure that the physical catchment is thoroughly represented. For example, where geology, channel behaviour, rules or economics controlling the operation of artificial influences are complex, or data requires local interpretation, appropriate local staff shall be consulted.

Any unusual problem flagged in earlier stages shall be brought forward and investigated during this stage.

The calibration results shall strive to achieve a 'best estimate'. Conservative assumptions may have to be used in the calibration, but a factor of safety should only be added in applying a model to a design problem and not to flood forecasting problems.

Calibrated parameter values shall be within physically reasonable limits. The model results shall not be unduly sensitive to changes in parameter values or the initial conditions of important model states where there is significant uncertainty about these.

Rainfall-runoff modelling

Further subcatchments shall only be created where the catchment response is not likely to be homogeneous, or where forced by model structure or input data availability. Where measurements are not available to calibrate a subcatchment, an appropriate analogue (based on hydrological similarity) shall be used as the initially estimated parameter set.

Model output shall not be unduly sensitive to the parameter values representing the separation of runoff from baseflow or the size of model stores (soil, groundwater stores, reservoirs and channels).

River channels

Seasonal or otherwise time-variant parameterisations shall only be used where they can be attributed to predictable physical phenomena. For example, in some river reaches, weed growth can cause water levels to increase by as much as 500mm during spring and summer, but this may not be predictable as it depends upon weather conditions and weed cutting programmes.

Model output shall not be unduly sensitive to the parameter values representing channel roughness or other routing coefficients, or downstream boundary conditions.

Abstractions and Discharges

Abstractions and discharges can be lumped together or represented individually. The representation of abstractions and discharges shall be determined by the significance of their impact on the water level as defined in the Agency's Good Practice for Flow Naturalisation.

Abstractions and discharges that are represented explicitly shall interact with the appropriate model store. Surface water abstractions shall be represented as outflows from the river network. Groundwater abstractions shall be represented as outflows from the groundwater store of the catchment model. Control rules imposed by the model shall reflect either the explicit control rules by which the abstraction or discharge is operated or implicit operational practice.

Model output shall not be unduly sensitive to the parameters used in translating groundwater abstraction to surface water impact, or in lagging surface water impact down the channel network.

Structures

Model output shall not be unduly sensitive to the weir/spill coefficients or bridge/culvert head losses for key structures.

Outputs

The deliverables of Stage 4 shall be:

- The validated model and associated data files
- Full documentation of the calibration and validation procedures.

STAGE 5: TESTING

Overview

The purpose of Stage 5 is to specify the requirements for test controlling for trapping potential problems associated with the verified models before their application in the real-time forecasting environment. The task of emulated real-time testing includes (i) synthetically generated scenarios to test the robustness of the models, (ii) violation of the inherent assumptions to test the stability of model results, robustness of model runs to a diversity of scenarios, and resilience of the model to severe test conditions.

Testing ensures that the model can be run in real time and can use an updating scheme assimilating gauged data to improve forecast performance. To run a model in real time, it must be able to interface to a source of real-time data, and the model-input data must be structured to provide guaranteed continuity of input data. This is usually achieved through 'graceful degradation' through a hierarchy of data (i.e. progressive averaging or in-filling of data in the event of drop outs to maintain system function, albeit with reduced accuracy).

Scope

The scope of Stage 5 is to produce tested models through emulating the real-time computational environment.

Input

Input to Stage 5 consists of the validated model. The report from Stage 4 shall specify the requirement for dynamic input datasets for testing if this has been specified by the Agency project manager.

Specification

Testing shall define the application of the updating scheme. A list of potential updating points shall be given with a preliminary list of points to be included within the scheme. Excluded points shall be justified. The type of updating to be applied (state updating, parameter updating, input updating or output updating/error correction), the parameter to be updated upon (flow, level, storage), any flow or level constraints placed on the updating scheme shall be defined.

For forecasting models, the performance of the tested model shall be compared against the required standard defined in the Inception Report and by reproduction of calibration or validation results (Stage 4).

Sensitivity analysis

The sensitivity of the verified model output shall be investigated to uncertainty in model the parameter representation and/or initial conditions using sensitivity analysis. This shall use the verified model but the sensitivity test can use calibration and/or verification data to make a pragmatic assessment. Sensitivity analysis shall be focussed upon those parameters that are expected to have a significant effect on the simulated behaviour of the system and for which there is uncertainty in the parameter values adopted. Therefore the parameters for which sensitivity analysis is required will vary with the catchment, available data and the model. The insight gained will enrich the future applications and conversely draw heavily on the modeller's experience of the model behaviour gained during the study. Generally, the poorer the data available for calibration/verification, the poorer the calibration and the poorer the match between calibration and verification performance, the greater the importance of sensitivity analysis.

Updating

Updating shall be used for all real-time forecasting modules, if this is technically feasible, unless it can be justified otherwise. The Contractor shall add updating routines once the model has been verified and accepted as a valid representation of the system.

The updating routine shall:

- update on the appropriate parameter(s),
- strike an appropriate balance between the number of updating points, the consequent improvement in model accuracy, and the impact on run time,
- deploy updating points in a ranked network that provides optimal improvements to model forecasts and applies corrections that are ordered to reflect the flow physics, and
- use good quality data to prevent erroneous corrections and correct errors in a consistent manner rather than merely correcting local measurement errors.

Prior to addition of the updating scheme and data hierarchies, the Contractor shall review the provisions made in the report of Stage 4. Any changes to the verified model shall be justified and agreed with the Agency for approval.

Run time

The runtime of the forecast model shall be sufficiently fast on the intended real-time platform to be suitable for operational use – i.e. it shall not be longer than the time interval within which significant changes in the state of the physical catchment may occur.

The performance of the forecast model shall be assessed through a continual process. The assessment and analysis used for the design model shall therefore be repeated for the forecast model, isolating the performance of the underlying design model from that of the model with error prediction and updating algorithms so as to permit evaluation of the improvement in performance by the updating scheme. Where the updating scheme is configured such that it is known that no improvement in performance will be made, the design model results can be reproduced without repeating the assessment.

Outputs

The deliverables of Stage 5 shall be:

- The tested model and associated data files.

- Full documentation of model and data files, to the standard specified in the S105 Specification (Appendix D).
- A report on testing of the model, highlighting any critical issues causing model failure, either in terms of accuracy or computational stability.

Report

The report on testing shall be thorough on any scenarios and associated input data used to investigate the problem to the same standard as that for the model warm-up, calibration and verification periods. The results shall be clearly documented with a single recommended course of action proposed. The test-controlling procedure shall reflect on the lead-time associated with the various scenarios. When real data is used during this stage, the full performance of the model shall be reported.

The 'critical success evaluation' shall assume that the model results are uncritically trusted in informing the actions that the model is intended to inform. It shall then assess how appropriate these actions would have been. Where operational triggers such as drought order triggers, flood warnings etc are quantified this assessment can be quantitative, based upon the variable that stimulates action. In other cases this assessment shall be qualitative.

Using the above quantitative and qualitative analyses, recommendations shall be made about under what conditions good and poor performance of the models can be expected, and why (including quality of input data sources). Potential improvements shall be prioritised and the anticipated improvement in model accuracy from the development indicated.

The report shall define which points are achieving the required accuracy and are therefore fulfilling the Agency's stated requirements. The report shall also specify the scope for the application of the tested model.

The further documentation shall be developed to help improvements to the model in the future. It shall also define the history of changes to the model, their costs, and the reduction in error gained. Doing this allows the Agency to understand the pattern of improvements (for example diminishing returns) and determine future investment in the model, or models generally.