Australian Rainfall & Runoff

A GUIDE TO FLOOD ESTIMATION

BOOK 7 - APPLICATION OF CATCHMENT MODELLING SYSTEMS

Australian Government

ENGINEERS AUSTRALIA

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PREFACE

Since its first publication in 1958, Australian Rainfall and Runoff (ARR) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The 3rd edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- prediction of extreme flood levels.

However, many of the practices recommended in the 1987 edition of ARR have become outdated, and no longer represent industry best practice. This fact, coupled with the greater understanding of climate and flood hydrology derived from the larger data sets now available to us, has provided the primary impetus for revising these guidelines. It is hoped that this revision will lead to improved design practice, which will allow better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of ARR. While the NCWE had long identified the need to update ARR it had become apparent by 2002 that even with a piecemeal approach the task could not be carried out without significant financial support. In 2008 the revision of ARR was identified as a priority in the National Adaptation Framework for Climate Change which was endorsed by the Council of Australian Governments.

In addition to the update, 21 projects were identified with the aim of filling knowledge gaps. Funding for Stages 1 and 2 of the ARR revision projects were provided by the now Department of the Environment. Stage 3 was funded by Geoscience Australia. Funding for Stages 2 and 3 of Project 1 (Development of Intensity-Frequency-Duration information across Australia) has been provided by the Bureau of Meteorology. The outcomes of the projects assisted the ARR Editorial Team with the compiling and writing of chapters in the revised ARR. Steering and Technical Committees were established to assist the ARR Editorial Team in guiding the projects to achieve desired outcomes.

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Status of this document

This document is a living document and will be regularly updated in the future.

In development of this guidance, and discussed in Book 1 of ARR 1987, it was recognised that knowledge and information availability is not fixed and that future research and applications will develop new techniques and information. This is particularly relevant in applications where techniques have been extrapolated from the region of their development to other regions and where efforts should be made to reduce large uncertainties in current estimates of design flood characteristics.

Therefore, where circumstances warrant, designers have a duty to use other procedures and design information more appropriate for their design flood problem. The Editorial team of this edition of Australian Rainfall and Runoff believe that the use of new or improved procedures should be encouraged, especially where these are more appropriate than the methods described in this publication.

Care should be taken when combining inputs derived using ARR 1987 and methods described in this document.

What is new in ARR 2019?

Geoscience Australia, on behalf of the Australian Government, asked the National Committee on Water Engineers (NCWE) - a specialist committee of Engineers Australia - to continue overseeing the technical direction of ARR. ARR's success comes from practitioners and researchers driving its development; and the NCWE is the appropriate organisation to oversee this work. The NCWE has formed a sub-committee to lead the ongoing management and development of ARR for the benefit of the Australian community and the profession. The current membership of the ARR management subcommittee includes Mark Babister, Robin Connolly, Rory Nathan and Bill Weeks.

The ARR team have been working hard on finalising ARR since it was released in 2016. The team has received a lot of feedback from industry and practitioners, ranging from substantial feedback to minor typographical errors. Much of this feedback has now been addressed. Where a decision has been made not to address the feedback, advice has been provided as to why this was the case.

A new version of ARR is now available. ARR 2019 is a result of extensive consultation and feedback from practitioners. Noteworthy updates include the completion of Book 9, reflection of current climate change practice and improvements to user experience, including the availability of the document as a PDF.

Key updates in ARR 2019

Update	ARR 2016	ARR 2019
Book 9	Available as "rough" draft	Peer reviewed and completed
Guideline formats	Epub version Web-based version	Following practitioner feedback, a pdf version of ARR 2019 is now available
User experience	Limited functionality in web-based version	Additional pdf format available
Climate change	Reflected best practice as of 2016 Climate Change policies	Updated to reflect current practice
PMF chapter	Updated from the guidance provided in 1998 to include current best practice	Minor edits and reflects differences required for use in dam studies and floodplain management
Examples		Examples included for Book 9
Figures		Updated reflecting practitioner feedback

As of May 2019, this version is considered to be final.

BOOK 7

Application of Catchment Modelling Systems

Application of Catchment Modelling Systems

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Chapter 1. Introduction

Mark Babister, Monique Retallick, Isabelle Testoni

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1.1. Scope and Intent

Catchment modelling has become the dominant flood estimation technique. This is because it:

- Allows different options to be simulated.
- Can be used with no data, limited data and in data rich situations
- Can be used to transfer estimations from one location to another
- Default parameters are available
- Well designed catchment modelling systems will reproduce flood behaviour over a range of floods
- A full hydrograph produced and can be used to assess storage
- Results can be easily visualised
- Is relatively easy to set up and reliable to do
- Can be reused by others for similar problems
- Helps to document the process of how the flood estimation was carried out

Scope is to provide practical guidance on the application of these models.

Because of the wide variety of flood estimation problems no modelling framework is suitable for all problems.

1.2. Application of guidelines

List types of problems the book is applicable to. Urban drainage design, detention basins, overland flooding, trunk drainage design, floodplain management, bridges and other infrastructure.

1.3. Specific Terminology

Generally the same terminology is used in this book as used elsewhere other than highlighting that while traditionally there has been rigid divide between hydrologic and hydraulic models the separation is largely artificial. Many components of a catchment model can be represented by either type of model. This book aims to guide the user in the application of a catchment model without predisposing which model is used to represent each of the processes.

An example of this divide is that routing does not only occur in hydrologic models and in this book when routing is referred to it includes routing in a hydraulic model.

A catchment modelling system refers a set of modelling processes or components that are used together to produce estimates of flood characteristics. These modelling processes can be available within a single modelling platform (such as a runoff-routing model) or can be the combination of a number of modelling platforms (where a runoff-routing model is used to generate inflows to a hydraulic model). Table 7.1.1 defines some key terminology for Book 7.

Table 7.1.1. Terminology of Book 7

Terminology	Description	Example
Modelling Process	Representation of conceptualised physical process in simulation models	Rainfall excess model, runoff-routing model
Modelling Platform	Software implementation of the modelling process (simulation model)	Software packages such as: RORB, RAFTS WBNM, MIKE SHE, TuFLOW, SOBEK, HEC-RAS, Spreadsheet software
Catchment Modelling System	Combines different modelling processes and may combine platforms	RORB to TuFLOW, or just RORB
Modelling Framework	Any statistical framework that is used to derive exceedance probability of flood characteristics from simulation model results	Ensemble or Monte Carlo framework

1.4. Relationship with other sections of Australian Rainfall and Runoff

This book draws together much of the advice and guidance in other books. Book 1 provides philosophy, Book 2 provides rainfall information, Book 3 provides alternative estimation techniques for comparison to results, Book 4, Book 5 and Book 6 provide theory and details on models discussed within this book. Book 8 deals with extreme flood and Book 9 deals with urban applications.

Chapter 2. Use of a Catchment Model

Isabelle Testoni, Mark Babister, Monique Retallick

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2.1. Introduction

A catchment model system is a very useful way of estimating how a system will perform under a number of different conditions. Catchment modelling systems are usually built from the series of modelling elements that are described in Book 4, Book 5 and Book 6. These are combined to replicate the key processes for a particular flood estimation problem.

The catchment modelling system can be used probabilistically (for estimating design flood behaviour) or can be used to estimate observed or historic flood behaviour. The catchment modelling system can be used to represent existing, historical or altered catchment conditions.

It is important when developing a catchment modelling system that the possible future uses of the model are properly identified so that the key processes are properly considered. The challenges in modelling are the need to represent various processes which introduces complexity, against the data available for calibrating these process and parameter and component interaction (Book 7, Chapter 3).

There are often subtle differences in how some of the key processes perform in frequent events than in rarer events. These differences mean that only rarer events can be used for the calibration which limits the data available for the calibration of complex models. Two simple examples are:

- during very frequent rainfall events the storage capacity of the soils is very important but during rarer intense events the rate of infiltration becomes more important ; and

- the hydraulics of a stream change significantly when flow moves from in-bank to the floodplain.

In both cases calibrating to just frequent events can give a very poor estimate of larger events.

In many modelling situations calibration exposes significant parameter interaction where very similar calibrations can be achieved with a range of parameters, while this often does not significantly change the behaviour of similar magnitude events it can make a significant difference to how larger events behave. When modelling components are combined into a catchment modelling system it is possible for this interaction to occur across modelling components. This problem is very common when only level data is available to calibrate a catchment modelling system that includes hydraulic and hydrologic components. A satisfactory fit can often be obtained for a range of flows and corresponding roughness values.

> Catchment modelling system results can be sensitive to the chosen parameter values. Different combinations of parameters can give the same answer at a single point. However as is often the case, when extrapolating to larger events they give different answers and very different representations of the flow behaviour.

In many situations it is never completely clear what the correct combination of overbank and channel Manning's n is. The following example shows the results from a simple hydraulic model where the overbank and channel Manning's n were selected to match the 1% AEP flow and level. While different combinations give identical results at the adopted 1% AEP level and flow they give very different velocity distributions. The cases also give very different level vs flow relationships for different sized events. This is one of the key reasons why its important not to adopt models for problems outside the range they were designed for. Figure 7.2.1 depicts the difference in conveyance, K (Book 6, Chapter 2, Section 7) for a range of levels. At extreme flows the conveyance ranges from 11 500 to 16 000 m^3/s. At lower levels the flow can double.

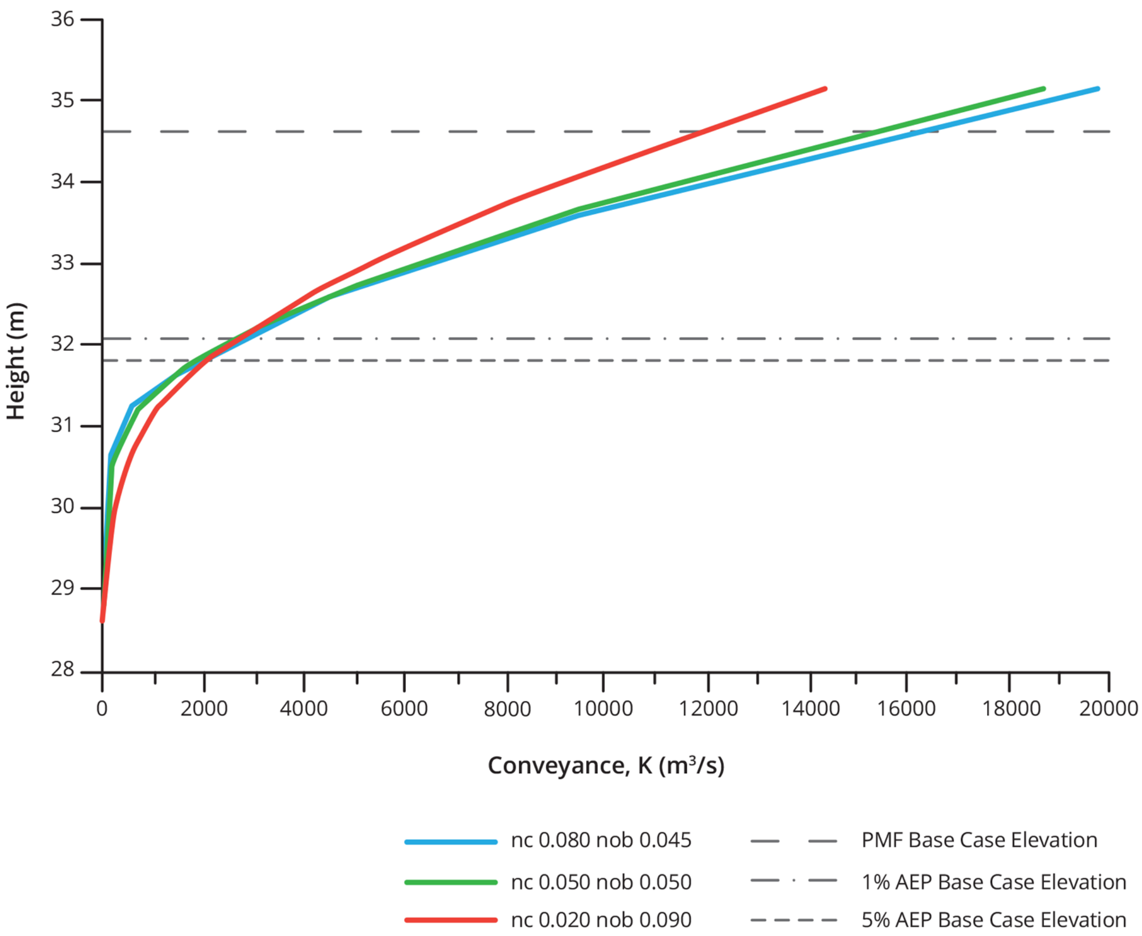

Figure 7.2.1. Conveyance Comparison – Different Manning's n Combinations

2.2. Overview of Modelling Applications

The application of a catchment modelling system should follow the process outlined within this chapter and book. While it is possible to create a catchment modelling system without following a rigorous process, it will lend itself to errors and wasted time in redoing work. A practitioner should first analyse the problem presented before deciding how to solve it. The data available must also be investigated, as it is likely that insufficient data exists for the ideal solution that the practitioner has already come up with.

A simplified overview of the steps involved in the application of a catchment modelling system (Figure 7.2.2):

- Conceptualisation of Modelling Approach (Book 7, Chapter 3);
- Developing a Catchment Modelling System (Book 7, Chapter 4);
- Testing Parameterisation, Calibration, and Validation of a Catchment Modelling System (Book 7, Chapter 5 and Book 7, Chapter 6);
- Application of Catchment Modelling System to a Specific Design Problem (Book 7, Chapter 7); and
- Interpretation of the Results and Understanding the Reliability and Uncertainty (Book 7, Chapter 9 and Book 7, Chapter 8).

These steps can be applied to an individual process, but it is important to apply them to the overall catchment modelling system. You need to confirm performance the overall CMS rather than just the individual components. Optimising individual components might not provide an overall robust CMS. The development of the CMS is constrained by the data that is available, the time/cost and experience of the practitioner.

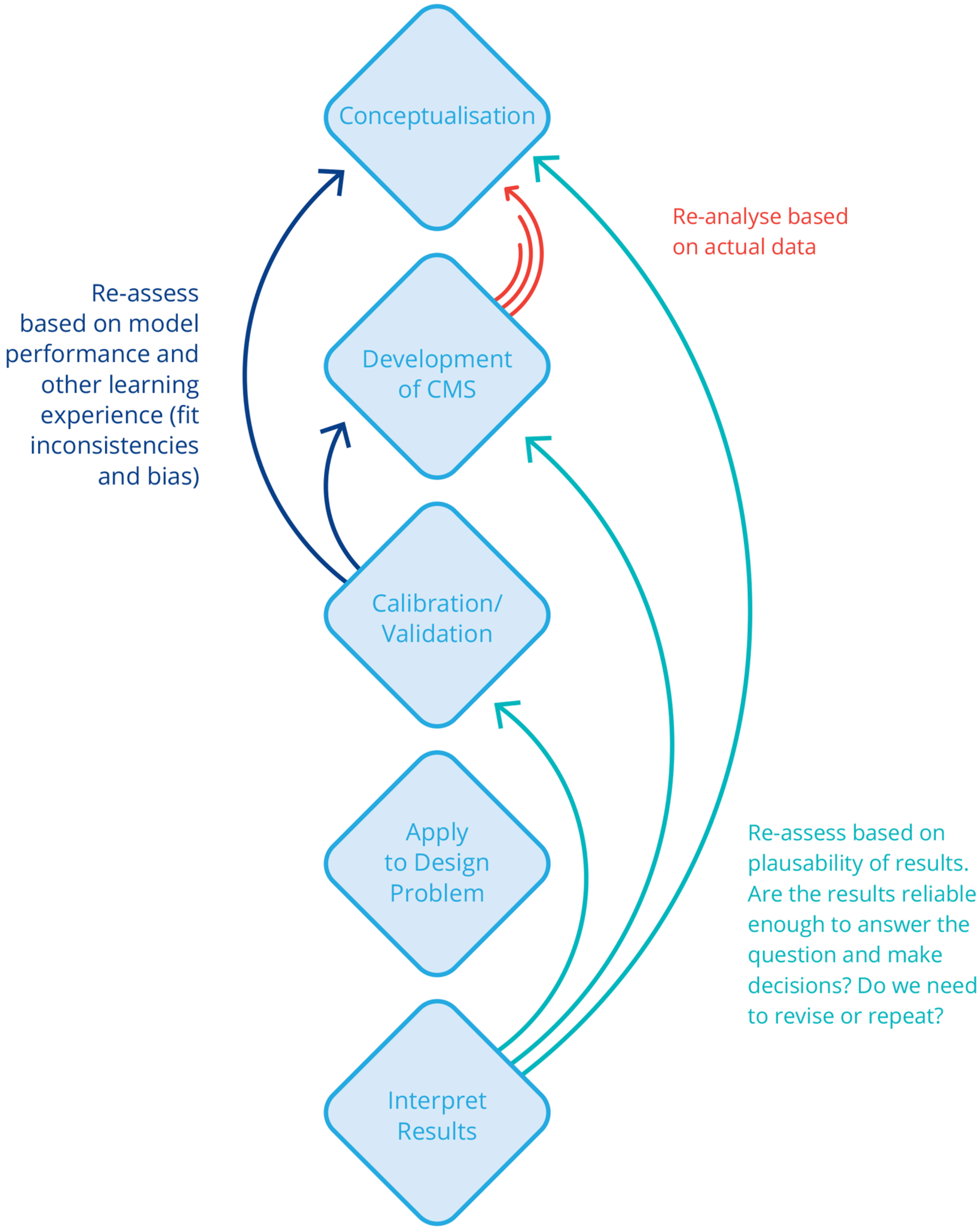

Figure 7.2.2. Steps in the Application of a Catchment Modelling System

Review of the conceptualisation of the catchment modelling system should be undertaken at each step in the process of creating and applying the catchment modelling system. This review does not have to be exhaustive. The reality is that most practitioners are undertaking this review as a sanity check already. It is highlighted here that this is a key step in the overall creation of a catchment modelling system or a component of it.

2.2.1. Conceptualisation of Modelling Approach

It is important at the start of a project to accurately define the problem and identify the key process/es that must be modelled in order to understand and accurately model the problem (Book 7, Chapter 3). In this stage limitations of the modelling approach must be explored. Available data, time, cost and model availability need to be defined for the problem in question. Preliminary selection of a catchment modelling system is carried out in this stage, though the selection may change as the practitioner develops the catchment modelling system.

2.2.2. Developing a Catchment Modelling System

The schematisation of a catchment in a modelling platform (Book 7, Chapter 4) depends heavily on the chosen modelling platform. Different modelling platforms have varied ways of representing the same catchment characteristics and features. In practice, the ease of representing key catchment features and key processes (discussed in Book 7, Chapter 3) plays a major role in developing a catchment modelling system. Decisions on conceptualisation and the representation of key features may be need to be revisited at this stage. Revising modelling platform choice is recommended if the initial selection is no longer appropriate in schematising the catchment.

2.2.3. Testing Parameterisation, Calibration, and Validation of a Catchment Modelling System

Ideally, all catchment models should be well calibrated and validated. However, data constraints mean this is not always possible or only limited calibration is possible. Book 7, Chapter 5 provides discussion on the best way to make use of the data that is available and discussion on data in general is in Book 1, Chapter 4. The calibration process of a model is not limited to matching historic records, but can include the overall estimation of parameters. The estimation of parameters aims to preserve the representation of the catchment characteristics as described by the conceptualisation of the catchment. Guidance on parameter values for ungauged catchments is provided in Book 7, Chapter 5. Validation techniques are used to independently test that the chosen parameters represent observed behaviour (Book 7, Chapter 6).

2.2.4. Application of Catchment Modelling System to a Specific Design Problem

Typically, at the start of setting up a catchment modelling system a specific design problem required a solution is already defined. Design applications of catchment modelling systems will vary depending on the specific problem under consideration. Book 7, Chapter 7 discusses different design applications after a catchment modelling system is established.

2.2.5. Interpretation of the Results and Understanding the Reliability and Uncertainty

The final step in the application of a catchment modelling systems is to provide information to decision makers, the community and designers regarding design flood behaviour. This information needs to be scrutinised and final checks should always be undertaken to ensure the modelled flow behaviour makes sense (Book 7, Chapter 8). Catchment modelling systems are only representations of the real world based on data and mathematical models.

Results can be inaccurate if any key processes or features are misrepresented in the catchment modelling system, which is not always easy to determine. This misrepresentation can be due to practitioner error, model error or incomplete and inaccurate data. The uncertainty surrounding design flood estimates should not be overlooked (discussed in Book 7, Chapter 9).

Chapter 3. Conceptualisation and Selection of a Catchment Modelling System

Monique Retallick, Isabelle Testoni, Mark Babister

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3.1. Introduction

A well thought out model conceptualisation and selection stage can result in significant project savings and the avoidance a lot of costly rework. While it is not possible to identify all potential issues, as learning experiences during a modelling project can identify issues and these can be addressed during this initial stage. This allows the limitations to be better understood and factored into decision making.

The conceptualisation stage in the catchment modelling process can be broken down into a series of steps that lead to informed decision making:

- Defining the problem under consideration and output needs;
- Identifying the key process/es that must be modelled to understand and model the problem;
- Identifying the available data;
- Selecting a level of modelling complexity that can be justified by the data available to calibrate or parameterise the modelling processes; and
- Selecting a modelling approach that matches these considerations with project constraints including, time, cost, model choices and modeller experience.

3.2. Factors for Consideration

The most important step in developing a catchment modelling system is to properly identify the problem under consideration, the purpose of the modelling and required outputs. Modelling is used to predict the behaviour of complex systems under different scenarios and conditions. Modelling will generally have a specific purpose. The purpose of modelling may include:

- Floodplain studies – inclusive of flood studies all the way through to mitigation impact assessment. This may include defining flood behaviour for land use planning.
- Flood Emergency Response – Model results can be used to enable emergency services to better prepare and respond to flood events by identifying potential flood hazard and planning evacuation routes. Model outputs can also enhance mapping outputs and improve flood intelligence for both responsible agencies and the community, leading to a reduction in flood impacts. Whilst not commonly used at present, it is possible that 2D models may be utilised more commonly for real-time flood warning in the future.

- Urban drainage studies – in such applications the hydraulic model may also perform the routing functionality typically carried out by a hydrologic model. The 2D model provides the “major” drainage layer and interfaces also with the “minor” drainage system (i.e. pits and pipes) dynamically;
- Dam Break assessments - Often a hyraulic model is used to route dam break hydrographs. 2D models are well-suited to this application as the flowpaths resulting from a dam break are often unexpected or different to typical flowpaths;
- Sizing of a spillway;
- Land filling for development;
- In any environment in order to assess the flood impact due to development;
- In-bank river flow modelling in 1D or 2D. This may be carried out in 2D in order to provide flow velocity that varies over the cross-section or in 1D in which velocity will be averaged over the cross-section. This approach is often used in ecosystem/habitat assessment;
- Wetland modelling - where routing paths are ill-defined and filling and draining processes are complex.
- Lake or estuary studies – often at the lower end of river systems the floodplain interacts with a lake or estuary and subsequently ocean or lake dynamics become important (tide, storm surge, or seiching).
- Water quality and sediment transport studies – these applications build on the two-dimensional hydrodynamics to provide information on water-dependent processes such as pollutant transport and river morphology.

Along with a specific purpose problems it is necessary to define the spatial extent and either the probability range of interest or parameter range. For example the spatial extents could be limited to just a dam, or a distance up and downstream. The following items should be defined at the start of the project:

- Spatial extent (note this might not be the same as the model extent);
- Probability extent (e.g. 5% AEP to 1% AEP);
- Parameter range;
- Types of outputs (flow, volume, level, rate of rise, warning time). These may be presented as either:
  - Peak;
  - Hydrograph;
  - Spatial Map; and/or
  - Animations.

The required outputs may be specified by the client, in the study brief.

While as part of the study a model of the entire catchment may be established typically a smaller specific location is the main focus of the study. If there are self-cancelling errors or bias in areas of the model not influencing the specific location of interest then the practitioner might not be concerned.

An important step in the conceptualisation of the problem is determining the likely scenarios that will need to be run (Book 7, Chapter 3, Section 2). For example if a future development scenario is to be run with urbanisation then a hydrologic model will be required which allows a change in pervious to impervious area.

3.2.1. Initial Scenario Identification

Along with defining the problem under investigation identifying, the types of scenarios that are likely to be assessed will significantly improve modelling decisions. For some problems the practitioner will only need to identify existing conditions. However for many problems the practitioner will be required to build a catchment modelling system that is capable of assessing different scenarios. Scenarios are broadly divided into these categories: modelling of historic and future conditions, mitigation options and management options. Most scenarios will fall into these broad categories. Some typical scenarios include:

- Existing conditions;
- Historic conditions;
- Change in landuse (impacts or restoration to pre-development conditions to manage the impact of urbanisation);
- Infrastructure (assessing and mitigation of the impact of a road and railway line);
- Structural flood mitigation measures (such as dam and levees);
- Future development scenarios;
- Change in dam operations;
- Changed catchment conditions assessment;
- Climate change;
- Parameter sensitivity tests; and
- Ocean interaction.

If the project requires only the definition of flood behaviour under existing conditions then this step can be ignored and focus is on the identification of key processes (Book 7, Chapter 3, Section 3). While in many situations, it will not be possible to identify all the scenarios at the conceptualisation stage that will need to be assessed, it is possible to identify the types of solutions, measures or works that are typically used to identify, mitigate or manage the problem. The ability to model scenarios is one of the powerful features of a catchment modelling system.

What Has Been Defined So Far

- The Problem;
- Likely Scenario (first pass);
- Spatial Extent (area of interest);
- Probability range or parameter range of interest

3.3. Identify Key Processes, Inputs and Mechanisms

The key processes and mechanisms in design flood estimation can include:

- Rainfall Models;
- Runoff generation;
- Overland flow;
- Hydrologic routing; and
- Hydraulic routing.

The key processes in flood estimation have been defined in Book 4, Book 5 and Book 6. The key design inputs have been defined in Book 2.

It is important to decide which key processes have the most influence on the scenarios of interest. For example, if the scenario of interest is land use changes then the key processes are runoff generation from different landuse types, catchment response from different land use types, resistance to flow for different landuse types. Therefore the chosen modelling platforms and catchment modelling system must be able to model these processes and allow for changes to parameters representing these processes.

3.4. Data Availability and Model Complexity

During the conceptualisation stage all data does not need to be collected. However an awareness of what data is or might be available will assist in the determination of which catchment modelling system should be used. Selecting the level of complexity of the model is a trade-off between data availability and predictive performance (Figure 7.3.1). Typically there is not enough observed data. Time and budget constraints are usually best addressed by reducing model complexity and the extent to which data is used.

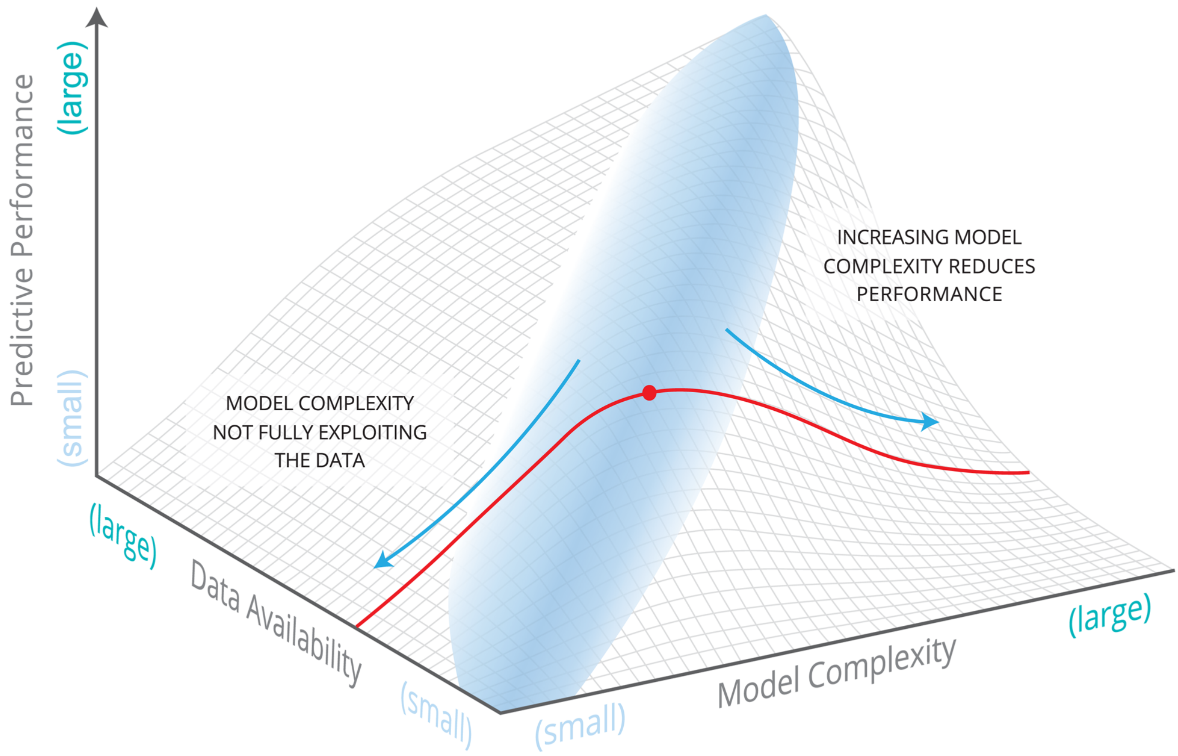

Figure 7.3.1. Conceptual Relationship between Data Availability, Model Complexity and Predictive Performance (Grayson and Blöschl, 2000)

Consideration must also be given to the resolution of modelling required. For example for a large catchment coarse representation may be sufficient. Therefore large subareas in the hydrologic model and a relatively large grid in the two dimensional hydraulic model may be used. For complex studies fine scale detail may be important and small grid and subareas may be needed in order to represent the hydraulic controls and key features.

What Has Been Defined So Far

An assessment of the available data and what can be achieve with it must be made. Following this some compromising on how key processes are represented must be made. It is a non-linear process.

3.5. Selecting Modelling Platform(s)

With a firm understanding of the problem, the key processes and data availability it is now possible to select a preferred modelling platform/s. A single modelling platform may contain all the key processes, inputs and mechanisms required to solve the design problem. However, in many cases is it more desirable to combine a number of modelling platforms. Reasons that influence the choice of modelling platform include:

- Reliable regional/default parameters for ungauged catchments (refer to Book 7, Chapter 5);
- Different modelling platforms are able to model specific features;

- Client preference;
- Standardisation;
- Likely run time;
- Anticipated resolution of the model and model outputs; and
- Ability to leverage existing modelling.

In many cases more than one modelling platform is often used. This is often the case where limited data is available as some modelling platforms are more suitable for ungauged catchments.

The other key inputs that must be considered at this stage are the project timeline, budget, experience with, and availability of modelling platforms. There is a certain art to modelling and there is no substitute for experience with a particular modelling platform. On many projects it is not practical to develop a job specific model and it is necessary to select one or a set of existing modelling platforms. This has major impacts on cost and timing. Likewise, selecting a modelling platform that the practitioner is familiar with can have significant impacts on cost timing and the reliability of results. Typically leading to a better outcome.

The advantages of selecting a platform that the practitioner is experienced with includes knowledge of appropriate parameter ranges, faster set up time, and knowledge of key features.

Selection of the Hydraulic Model

The selection of the appropriate type of hydraulic model is a critical decision in the application of catchment modelling systems process. In this step the physical system flow behaviour, which can commonly involve complex highly turbulent flows, must be reduced to an equation, or set of equations, describing the main characteristics of the flow. Here assumptions have to be made as to whether the flow can be considered as being one-dimensional (1D), two-dimensional (2D), or a combination of both, and whether the flow can be described as being steady (ie. constant with time), or unsteady (time-varying). In virtually all rural or urban floodplain modelling, vertical accelerations in the flow field are considered to be negligible and a hydrostatic pressure distribution is assumed, with computations and results based around a depth-averaged velocity. Further details are provided in Book 6, which outlines the governing equations utilised in hydraulic models. More detail on the application and selection of a hydraulic model is provided in Australian Rainfall and Runoff Supporting document – Two dimensional Modelling of Rural and Urban Floodplains (Babister and Barton, 2016).

What Has Been Defined So Far

A catchment modelling system has been chosen for the defined problem which makes the best use of available data. Consideration is given to model complexity and model representation of key processes.

3.6. References

Babister, M. and Barton, C. (eds) (2016). Australian Rainfall and Runoff Support Document: Two dimensional modelling in urban and rural floodplains. Project 15

Grayson, R.B. and Blöschl, G. (2000), Spatial Patterns in Catchment Hydrology: Observations and Modelling. Cambridge University Press, p: 404

Chapter 4. Catchment Representation in Model

Mark Babister, Monique Retallick, Erwin Weinmann, Isabelle Testoni

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4.1. Introduction

Once a catchment modelling system has been conceptualised and modelling platforms have been selected it is necessary to represent the catchment and floodplain in the modelling platforms. This requires a series of important decisions where all the key features and previously identified processes need to be represented. Model selection may need to be revised once data collection and analysis is undertaken. This chapter outlines all the key steps in establishing a catchment modelling system.

Schematisation of a catchment modelling system includes representing any physical properties of the catchment that affect the catchment's flood response. The selection of a catchment modelling system (Book 7, Chapter 3) will influence how the practitioner will schematise the catchment and its floodplain. Some catchment modelling systems are inherently easier to schematise certain key processes and features and therefore the ease of schematisation between different modelling platforms should be taken into account when selecting a modelling system.

The guidance within this chapter is divided into generic catchment modelling systems and that specific to hydrologic model and hydraulic models for ease of use.

4.2. Adapting an Existing Model

This is the most common mistake that practitioners and clients make. While it may be an easy choice from a time and budget perspective to choose to modify an existing model this often leads to a poorer representation of flood behaviour. Before making the choice to adopt an existing model consideration must be given to the original purpose of the model and how key processes relevant to the current design problem have been represented in the model.

Typical problems include:

- The original model was calibrated for a range of frequent floods and is not suitable for very frequent floods (or vice versa);
- the model might represent the processes for the existing case but cannot be adapted easily for new scenarios (changed catchment and floodplain conditions) that need to be run; and

The model is calibrated for rarer events and a different mechanism is dominant for smaller flows.

4.3. Data

The amount of historic data and terrain information available for the development of a catchment modelling system has a large impact on the model establishment. Book 1, Chapter 4 provides a detailed discussion of the types of data available and issues that the practitioner should look out for when using the data. Book 4, Chapter 2 discusses the balance between data availability and model complexity.

4.4. Key Features of a Catchment

In the conceptualisation and model selection stage the key features of a catchment should have been identified along with key processes. When developing a catchment modelling system the practitioner needs to ensure that they key features are properly represented in the model. A list of possible key features are:

- Landforms, vegetation and land use catchment areas influencing runoff response;
- Streams, stream network, floodplains and overflow paths;
- Natural and man-made flow constraints;
- Natural and man-made storages;
- Roads and railway lines;
- Weirs;
- Flow structures including levees, bridges and culverts;
- Levees;
- Flow diversions;
- Pits and Pipe network;

There are different ways of representing these key features within a modelling platform. Sometimes there are multiple options and it is important to select the method of representation that best suits the problem. Key features are identified so that most of the model effort is focused on them instead of other features that don’t have a material effect on flow behaviour.

> There is a temptation to spend modelling effort on those features that can be readily measured. Yet it is often that the features that are hard to measure and quantify have a significant effect on flood behaviour. For example in a large river model small culverts will have little effect on flood behaviour.

4.5. Time step

Time step is typically more of an issue with hydraulic modelling, however, it is also an issue for some hydrologic processes. For example the time step at which a loss model is applied can change the amount of rainfall excess. Too coarse a time step will mean that the runoff hydrograph will be too coarsely represented. Continuous simulation models often need to be run at a finer time step to capture important details for simulating floods. Most hydrological processes (unless spatially distributed) the time step it is not a problem and computationally is no longer a challenge. For two and three dimensional hydraulic models this can still be a computation time issue.

4.6. Boundaries between Models Elements and Platforms

A key decision that has to be made is where the boundary is between modelling elements and platforms. The common example is between a hydrologic and hydraulic model. A model boundary usually means that there is no feedback between the modelling platforms. It is also important to understand at this point you could be using a very different modelling approach to represent the same process.

> A common problem is at the boundary between a hydrologic and hydraulic model. At the boundary care should be taken to ensure that there is no double routing of a flow hydrograph.

4.7. Hydrologic Modelling

As discussed in earlier chapters, the actual processes involved in converting rainfall inputs to a catchment into runoff and eventually a flood hydrograph are very complex, and they are represented in modelling platforms in a highly conceptualised form. The first decision to be made in representing a catchment is the level of spatial resolution to be adopted. At each level of resolution, from lumped models to fully distributed models further decisions then need to be made on how the key processes are to be represented in the model. In practice these decisions generally come down to selecting first an appropriate model platform and then possibly a particular model version.

4.7.1. Spatial Resolution

The appropriate degree of spatial resolution to be adopted in a hydrologic catchment model depends on the following factors:

- Catchment size
- Degree of spatial variation in catchment rainfall
- Variation in land use characteristics
- Presence of natural features or man-made structures that have a major influence on flood formation and need to be represented in the model
- Range of flood magnitudes to be simulated
- Requirement to estimate flood characteristics at internal points in the catchment

4.7.1.1. Lumped Models

In relatively small catchments there is often only limited spatial variation in rainfall and loss characteristics, and it is thus acceptable to treat the catchment as a homogeneous unit. In such situations, and when there is only interest on the flood hydrograph at the catchment outlet, a lumped model can give acceptable results.

While lumped flood hydrograph estimation models have the advantage of simplicity, they are limited in their application to the following situations:

- catchments with relatively uniform spatial rainfall, loss and baseflow characteristics or where the variation of these characteristics between events is relatively minor, so that the derived unit hydrograph or other model parameters are applicable to a range of design events

- catchments with no significant artificial storages (reservoirs or flood detention basins)
- applications that do not require extrapolation to the range of Very Frequent or Very Rare to Extreme floods.
- applications where a flood hydrograph is only required at the catchment outlet, as for the design of drainage structures on roads and railways

As lumped models do not represent the internal structure of the catchment explicitly and do not have direct links to physical catchment characteristics, they depend on the availability of observed flood hydrographs for their calibration. The scope for application to ungauged catchments is thus more limited.

4.7.1.2. Semi-distributed Models

Semi-distributed models allow the spatial variation of inputs and key processes to be modelled explicitly. This is particularly important in large catchments and in catchments where the natural flooding characteristics have been significantly modified by various forms of development, including the construction of reservoirs, flood mitigation works and transport and drainage infrastructure.

Most of the modelling platforms in common use in Australia belong to the group of semi-distributed models, owing to their flexibility and efficiency in representing the key factors that determine the flood formation under a broad range of catchment conditions. As explained in more detail in Book 5, Chapter 2 and Book 5, Chapter 6, the catchment is represented in the model through a network of nodes and links.

It is important that the development of the network structure used in the model is guided by a good understanding of the key catchment features described in Book 7, Chapter 4, Section 4. The catchment subdivision into model subareas should follow topographic features and match the degree of variation of the key influencing factors (spatial rainfall variability, soil and land use characteristics). The conceptualisation and level of detail in the representation of the flood producing and flood modifying processes (Book 7, Chapter 4, Section 7) should reflect their relative importance and their influence on the flood hydrograph outputs.

In large catchments the distributed runoff inputs experience a large degree of smoothing as they are combined and routed progressively through the stream or channel network to the hydrograph output location. This means that recorded flow hydrographs at the catchment outlet will provide only limited information on the flow contributions from different parts of the catchment and the influence of individual catchment features. However, the role played by different catchment features in the formation of flood hydrographs can be expected change for different flood magnitudes, and this needs to be reflected in the catchment representation.

Difficulties in calibrating a model to observed flood events of different magnitude should be taken as an indication of the changing role of processes, and the model representation thus needs to be adapted accordingly. In many cases a significant change occurs between floods that are mostly contained within the stream channel and floods in which floodplain storage plays an important role in the routing process. Large floodplain storage areas may need to be represented by special storage elements whose characteristics and parameters are determined from hydraulic calculations.

For more detailed guidance on the representation of catchments in node-link type models users should consult the user manuals of specific modelling platforms.

4.7.1.3. Distributed Models

In the fully distributed or grid-based flood hydrograph estimation models the catchment is represented by a large number of grid cells, based on topographic data from a digital elevation model (DEM), supplemented by more detailed survey information on the drainage network and the flow controlling features of the catchment. The two-dimensional hydraulic modelling approach adopted in these models allows their application in quite complex flow situations, e.g. floodplain areas with ill-defined drainage networks or urban areas with many flow obstructions.

In principle, distributed modelling allows the influence of spatial variability in rainfall inputs, runoff production and routing characteristics to be captured in more detail than in node-link type models. However, for this potential to be fully realised, the conceptualisation of the runoff producing processes has to be well matched to the scale of the basic model elements (grid cells) and has to reflect the change in processes as the cells are wetted up and the flow efficiency increases with flood magnitude.

The capabilities and limitations of distributed (rainfall-on-grid) models are further discussed in Book 5, Chapter 6, Section 5.

4.7.2. Process Representation

As explained in Book 4, Chapter 3, all models applied in flood hydrograph simulation employ a highly conceptualised representation of the actual hydrologic processes involved in runoff production and routing of the runoff inputs from the different parts of the catchment to form hydrographs at points of interest. It has to be kept in mind that the adopted conceptualisations are intended for the the simulation of probability-based design flood events rather than actual flood events. The model should reflect the typical flood response of the catchment to be expected in future events but may not reproduce the full range of variability between actual flood events.

In the event-based flood estimation methods, the influence of all the pre-event rainfall is only reflected in the initial catchment conditions (that determine initial loss), and in the delayed runoff contribution from baseflow which is modelled separately. The event rainfall is then divided into rainfall loss and rainfall excess which produces the surface runoff component that is modelled in detail.

The detailed guidelines for modelling losses and baseflow are provided in Book 5, Chapter 3 and Book 5, Chapter 4, respectively. The different approaches for modelling the production of runoff hydrographs from model subareas and for routing these through the drainage network to points of interest are discussed in Book 5, Chapter 6.

4.8. Hydraulic Model Establishment

The text below is largely reproduced from Babister and Barton (2016) which is focused on two dimensional modelling. Two dimensional models are used for the majority of problems because they provide spatial output showing the extent of flooding and flood characteristics. There is however a place for one dimensional models where a fast reliable computational model is required for flood forecasting or Monte Carlo modelling. More detail can be found in Babister and Barton (2016).

4.8.1. Model Extents

The primary goal in selecting a model extent is to represent key processes within the area of interest without significant influences driving runoff-routing or hydraulic behaviour from areas outside the model extent. Key considerations include, but not limited to:

- Ensuring that the model extent is sufficient to cover the likely inundation extent of the largest event to be modelled. The key here is that for the largest event to be modelled (typically the Probable Maximum Flood), the model extent does not artificially restrain water movement at its boundaries, and that the topographic data within the model extent also extends beyond the inundation areas. For a hydrologic model the model must cover the contributing area.

- Ensure that boundary conditions are located sufficiently far away so as to not unduly influence results within the area of interest.

- Minimise the inclusion of unnecessary (flood-free) areas, as this produces excessive results, impacts on computer memory requirements, increases model output file sizes and reduces efficiency.

If the likely maximum extent of the inundated area is difficult to define (e.g. very flat terrain or dam break studies) defining the extent can be an iterative procedure. A recommendation is to always start with a large model area and then narrow the model domain based on feedback of model results, as this is far less problematic than the reverse process. Using a coarser grid/ mesh resolution to reduce run times during these earlier stages of the modelling process can be an effective and efficient approach, especially for large model areas. Run time is typically not an issue for hydrologic models other than distributed runoff-routing models.

Model Study Area vs Model Applicability Area

In most cases there is a difference between the model extent and the area that the model can be used to produce reliable results. Just because a model extends over a certain area does not mean reliable results can be extracted in all areas of the model. Often these fringe areas are modelled just so that the model boundary conditions are sufficientlyfar away from the study area.

4.9. Boundary conditions

Boundary conditions should be located a sufficient distance away from the location of interest so as not to influence the results. The practitioner must decide which type of boundary condition to apply.

Beware of direct rainfall boundary conditions and pre-wetting of catchment.

When using direct rainfall water is applied to every grid cell so all calculation points are located on a boundary. A common problem is that the depression storage within the model which can be a combination of numerical and actual can be overlooked when applying losses.

4.9.1. Location of Boundary Conditions

The location of the boundary conditions is of critical importance. In general, boundaries should be located as far away from the study area as is practicably achievable. Any boundary condition on a hydraulic model requires a description of the water level, flow rate and velocity, flow direction and water surface slope across the boundary. In most situations, these flow conditions are rarely available as input data time series. Consequently, a range of assumptions are made in the definition of these conditions. While some models provide the ability to specify these explicitly, most models have generic assumptions incorporated into the model system to facilitate the automatic calculations of the range of parameters required.

As an example, the water level at a boundary condition is typically defined as a time series of recorded level. The other flow conditions are assumed or calculated based on the general assumptions or pre-defined conditions, such as an assumed flow direction across the boundary and assumed water surface slope. In this example, these assumptions, when combined with the water level time series, allow a discharge to be estimated across the boundary.

The specification of these conditions on the boundary introduces errors into the model predictions. Over time, these errors propagate through the model domain and may eventually pass through the model domain and out through another boundary. In a well developed and tested model, these errors become dampened as they propagate through the model domain. If the boundary conditions are located remotely then the errors become insignificant at the area of interest.

As an example, if a high flow rate is introduced through a topographic boundary condition that has small conveyance (restricted flow capacity) then high velocities and a significant velocity head results. This may cause large errors in the momentum flux into the system leading to errors in the flow patterns, water level and velocities downstream from the model boundary into the model domain. In this case, provided the boundary is located well away from the area of interest so that these effects have fully dissipated, the presence of these unrealistic flow patterns can be considered acceptable for the purposes of the investigation.

4.9.2. Type of Boundaries

The types of boundary conditions that are applied are important in determining the results produced by the model. The boundary conditions can be defined into two broad categories of;

- External boundary conditions; and
- Internal boundary conditions.

The most common boundary conditions applied in hydraulic models are external boundary conditions with a flow or discharge boundary defined along the upstream boundary of the model and a water level defined at the downstream external boundary.

The boundary condition type can be described using one of the following for specifications:

- Flow time series specified which is distributed across the model boundary grid/mesh points;
- Water level time series which is assumed to be constant across the model boundary;

- Flow and water level specified in combination as an input time series and distributed along the boundary;
- Flow or water level specified as a one dimensional line of values along the boundary for each time step;
- Transfer boundary where the water level, flow, velocity and water surface slope are provided from another model; and
- Rating curve along a model boundary (combination of water level and flow).

The combination of boundary types is important and must be considered in combination with the specification of initial conditions. In general, the boundary conditions for hydraulic models should be designed with upstream inflow or discharge boundaries and downstream water level boundaries. This ensures that any errors or uncertainties associated with initial conditions are “washed out” of the model. If other combinations of boundary conditions are used then the initial conditions will not necessarily be “washed out” of the model. The initial conditions will then significantly affect model simulation results and the results may not be reliable.

4.9.2.1. External Boundary Conditions

The schematisation of the external boundary conditions can vary across the range of model types and even within specific modelling platforms. The schematisation of external boundary conditions is therefore highly dependent on the specific case and modelling platform being used and it would be inefficient to describe all types of boundary conditions in detail. However we can define some general principles for schematising boundary conditions that are important to consider.

If general the practitioner should approach the schematisation of external model boundary conditions in a similar manner to how a boundary condition would be conceived for a physical model. The practitioner should consider the physical flow characteristics at the boundary in the real world and should attempt to schematise so as to minimise any artificial flow behaviour that is induced by the boundary condition. Issues that should be considered include:

- Align the model grid to be normal to the boundary flow streamlines if possible;
- Avoid rapid transitions in flow regime at the boundary;
- Avoid placing the boundary where turbulent flows are likely to be crossing the boundary;
- Minimise the wetting and drying on the boundary if the flooded boundary changes in width substantially during the simulation;
- Ensure that the boundary condition does not restrict or expand the flow substantially at the boundary; and
- Preference for specifying an upstream inflow discharge boundary and a downstream water level (or rating curve) boundary in combination.

As discussed, the boundary conditions should be located as far from the area of interest as possible. This will minimise the possibility of boundary effects and errors influencing the model results within the study area. The specification of the boundary conditions will therefore have a significant influence on the grid/mesh resolution. In general, the boundary condition should be identified as the first task that is carried out when conceptualising and schematising a model.

4.9.2.2. Internal Boundary Conditions

Internal boundary conditions are specified to control either the flow or the water level at grid/ mesh element(s) within the model and not along the edge of the model grid. There are generally two types of internal boundary conditions:

- Internal inflow points (sometimes called sources or sinks); and
- Internal flow or level controls.

The primary issue in defining internal inflow boundary points is to ensure that the flow rate is compatible with the grid or mesh resolution. There should be sufficient conveyance into or out of the element(s) where the boundary condition is specified to allow the model to accept the flow without introducing significant disturbance to the natural flow streamlines. If a large flow is forced as a boundary through a relatively small cell element with limited flow area; the model will produce an excessively large velocity and water level gradient to achieve continuity with the flow volume. If this occurs then significant momentum can be artificially introduced to the model at this location which will then influence water levels and flow patterns for a relatively large distance away from the boundary cell.

Internal control boundary conditions are a special form of boundary condition and are generally not recommended unless there is a strong compelling case for their use. An internal boundary condition will force the model to reproduce a predefined hydraulic behaviour within the model domain. The most common internal boundary condition is a forced rating curve at an internal cross-section of a one dimensional model. These boundary conditions are highly “reflective” and will introduce distortion and disturbance of the flow behaviour far from the actual boundary point. It is not recommended the use of this type of boundary for most catchment modelling applications.

4.10. Run Times and Computational Resources

The availability and type of computational resources will impact directly upon the efficiency and timeliness of any project. The efficiency of a gridded model study will be greatest where model run times are less than 24 hours. The shorter the run time the greater the efficiency. However, depending upon the extent and resolution of the model and the length of the modelled events there may be situations in which run times may be in the order of several days.

Excessively long run-times can introduce a significant bottle-neck in the study timeline and the decision to accept an excessively long model run time should be made carefully. Timeliness may be particularly affected during the calibration phase, where a large number of iterative simulations are necessary, mostly in series rather than parallel. With excessive run times the calibration essentially relies on the skill of the practitioner and their knowledge of likely calibration parameters.

In addition, the total number of runs required can be an important consideration if there are many scenarios to be considered, such as different event durations and Annual Exceedance Probailities, development scenarios, blockage scenarios or scenarios to parameter sensitivity tests (refer to Book 7, Chapter 7, Section 2). During the planning stage, the practitioner will need to consider the following factors to estimate the efficiency and timeliness of the study.

- The estimated length of time required to complete each run;
- The number of calibration and design events to be simulated;
- The number of computers/processors available;
- The ability of the computers to undertake multiple runs in parallel or not; and
- The number of licenses available if proprietary software is to be used.

The type and availability of computational resources can provide a real practical constraint. It may limit the number of design runs that can be achieved, the length of event that can be simulated, or the achievable resolution of the model. Such limitations and the resulting implications need to be identified as soon as possible in the process.

Consideration of run times can be particularly important for rural flood studies, or for studies involving continuous simulation of long flow periods. Such studies may require simulation of floods or flow sequences lasting several months. In these situations it may be appropriate to consider the use of a modelling package that can implement an adaptive timestep, using a longer timestep during periods of relatively steady flow conditions, which may significantly reduce computational run times. Adaptive timesteps are discussed further in Book 7, Chapter 4, Section 12.

The fast run times of hydrologic models lend themselves to Monte Carlo modelling. However, run times of two dimensional hydraulic models are somewhat prohibitive at this point in time. Fast run times are possible one dimensional hydraulic models. One alternative is to Monte Carlo or Ensemble hydrologic models then apply a selection of events to the two dimensional hydraulic model. Book 2, Chapter 5 recommends running an ensemble of ten temporal patterns in a hydrologic model and the selecting the pattern closest to the average (flow or volume depending on the problem of interest) through a hydraulic model.

4.11. Model Resolution

All models represent different processes at different resolutions:

- *One Dimensional Hydraulic Models* - the resolution is based on the space between cross-sections; and
- *Two Dimensional Hydraulic Models* - it is a simple representation of the topography.

Given other considerations such as run time it may not be possible to have the model resolution fine enough to represent the key features in the perfect detail. It is sometimes necessary to compromise on model resolution. For example, A levee is 30 m wide but chosen cell size is either 20 m or 40 m. Engineering judgement should be applied to decide which cell size should be used. An adjustment to the resolution of the model may be required in order to properly represent the flow behaviour.

4.12. Time Step

The model simulation time step is dependent on the model grid/mesh resolution and the schematisation of features in the model. As a consequence, the impact of poor model schematisation can lead to inefficiently small time steps which in turn will produce excessive run times. The impact of excessive run times should not be underestimated and in practice it becomes impractical to calibrate and apply the model effectively.

There are generally two choices for selecting a model time step which are:

- A fixed regular time step; or
- An adaptive time step.

The fixed regular time step allows the practitioner to pre-determine the model run time and to set the saving step (in which model results are saved) as a regular multiple of the simulation time step. However, the time step will need to be set at the shortest time interval necessary for stability of the model during the most energetic or deepest flows during the simulation. This typically occurs for only a very short period of time during the peak of the flood hydrograph. Consequently the model simulation time is longer than is necessary as it is fixed for the entire simulation. However, the practitioner can be sure that the simulation will complete within predetermined run time.

The adaptive time step allows the model to determine the appropriate time step necessary to maintain stability as defined by the Courant condition. The practitioner will typically set a maximum and minimum time step allowable. This allows the model to time step at relatively longer time steps when the flow is shallow or less energetic and shortens the time step during the peak of the flow event. In theory, this should allow the shortest run time for the simulation to be achieved whilst maintaining model stability. However, in practice the adaptive time step method can often lead to excessively long run times. This is due to the impact of a few minor locations in the model where short lived energetic fluctuations in the flow can lead to the minimum time step being selected for excessively long periods of time.

Run times can also become excessive if the period that it takes for the flood wave to propagate through the model is very long. For example, simulations of large river systems or of flat terrain where the critical rainfall duration is long, will have propagation times in the order of days, if not weeks. However, small catchments with short critical durations may only have propagation times in the order of hours. Therefore, some idea of the likely propagation period is needed before finalising the model resolution and extent.

4.12.1. Save Step

The model save step is an important issue to consider during the model schematisation process. As models (particularly hydraulic models and distributed models) will typically produce very large results files if all the results are saved, there is a requirement to select an appropriate saving step for the results.

The model saving step needs to be sufficient short to be able to define the shape of the hydrograph in time. The model save step also needs to be sufficiently short to enable the observation of stability issues that may occur during the simulation. If a model is being saved at a longer time interval than a higher frequency oscillation in the model then it would not be easily identified and could be missed. It is important that the model is checked thoroughly by saving all time steps at specific points or at small regions in the model domain. This allows for the observation and checking of stability issues without the need to save the entire model at all time steps. It is generally impractical to save all results at all time steps in a 2D model and it will typically exceed the limitations of most computer storage and hardware to do so.

4.13. References

Babister, M. and Barton, C. (eds) (2016). Australian Rainfall and Runoff Support Document: Two dimensional modelling in urban and rural floodplains. Project 15

Chapter 5. Determination of Model Parameters

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5.1. Introduction

Following the selection of the catchment modelling system and the catchment and floodplain representation required, the next step is the estimation of appropriate model parameters to apply to the model platforms in the required application.

A flood model is a representation of the physical catchment processes affecting floods and the implementation is defined by a parameter set to apply the model to the specific problem being considered. The estimation of these parameters is often referred to as the calibration process.

While the term calibration strictly applies only where there is observed data to calibrate against, in this chapter calibration is defined here in general terms as the process for determining appropriate model parameters for the hydrologic and hydraulic models to ensure that they can be applied to the design flood estimation problem being considered. It involves varying model parameters to ensure that model results match observed data, to confirm that the model is performing adequately and is consistent with the records. Calibration can be carried out in a variety of ways and this chapter discusses appropriate methods of calibrating hydrologic and hydraulic models.

While the models used for these applications will generally have some representation of the physical characteristics of the catchment, meaning that the model parameters should be based on these physical features, there will always be uncertainty and the parameters will need to be estimated using available data to ensure that the model is at least consistent with the observed catchment performance. If the model represents physical processes closely, parameter values could be measured from catchment characteristics, but this is an uncommon situation.

The parameter estimation process may be based on recorded data (if there are suitable records in the project area) or may be based on regional estimates if the local catchment is ungauged or data is limited. There is a gradation between these two extremes however, it is rare that there is absolutely no available information to assist in setting parameters. It is also rare to find that there is sufficient data to allow a precise parameter determination, so the objective in determining parameters is to ensure that as much data as possible is used in this exercise.

Flood investigations usually require both hydrologic (calculation of design flood discharges) and hydraulic (calculation of flood levels, velocities and flow distributions as well as design of drainage systems) modelling applications, so this chapter covers both of these.

This chapter describes the different approaches to determining model parameters for the range of flood investigations and for the different amounts of available data.

5.2. Overview

The approach to parameter determination will depend on a number of factors which will determine the approach to the calibration and the level of detail sought in the process. This includes the model platform and the design problem.

5.2.1. Physical basis of model

Some models platforms may be purely ‘black-box’ or heavily conceptualised mathematical representations of the physical processes while others are more directly based on actual physical processes. Parameter estimation will be based on measurable catchment characteristics for model platforms where there is a direct physical basis for the parameters, and in these cases it is easier to establish model parameters. Most model platforms are likely to have at least some physical basis; it is thus possible to establish an acceptable range for model parameters, and model parameters calibrated to observed data should only be allowed to vary within this range.

During calibration, the parameters that are physically based should be defined using the catchment characteristics, while the other parameters can be varied so that the model results match the observed data, ensuring that the values remain within reasonable and acceptable limits.

The sensitivity of model parameters is also variable and some parameters have a greater influence on the model output than others. In some cases, there may be inadequate data to allow an accurate determination of actual parameter values. Therefore, these parameter values must be set using knowledge of model and catchment processes. There is a concern though that some parameters (e.g. Non-linearity parameters in runoff-routing models) may be important in design situations where rare floods are to be modelled but the observed data does not include any floods of the required magnitude. Therefore these parameters may appear insensitive during calibration but they have a major influence in the design situation.

5.3. Guiding Principles

Establishment of and applying models will vary depending on particular circumstances. However, for flood estimation applications, the following guiding principles will apply:

- All Available Data both formal and anecdotal should be considered in the calibration and the best use should be made of this data, in-line with its assessed accuracy and reliability. This data is the only way to ensure that the model application can be consistent with available local information. It is also important to carefully review the data to ensure that it is consistent and there are no obvious errors that will affect model performance.

- When calibrating the model parameters, it is important that the practitioner has an understanding of the role and relative importance of the different parameters and how they influence model operation. During calibration it is then important to concentrate on the most influential parameters, especially those that affect the model performance in the areas of particular concern for the specific model application.

- Model parameters when fitted to the data should be reasonable and within the range expected for the model platform and should be consistent with the physical features of the catchment being considered. If parameters are not within this typical range , the model conceptualisation could be incorrect and while the model may appear reasonable during calibration, there will be serious concerns for design events modelled where the event magnitude is run outside the range of that used for calibration. It is also possible that parameters outside the typical range may indicate errors in the observed data, and the calibration may be attempting to fit the model to these errors. The data quality and consistency then needs to be reconsidered and the calibration reanalysed accordingly.

Even if the data is of poor quality and incomplete, it is important that the model calibration be at least consistent with the available information, especially local or anecdotal information where formal data collection is lacking. Even very poor quality observations may be sufficient to apply a ‘common sense test’ and to ensure that even an essentially uncalibrated model can be a reasonable representation of local conditions.

5.4. Parameter Determination for Catchment Modelling Systems

5.4.1. General Approach

This section provides guidance on the parameter estimation for model platforms (both hydrologic and hydraulic models). Many principles are the same for these two calibration processes, but there are some differences in the data and approaches.

There are four basic approaches that will normally be dictated by the available calibration data and sometimes by the project budget and timeframe, and this classification is not as simple as the division into gauged or ungauged catchments.

The four primary categories are:

a. *No Data* - This is the lower limit to data availability, and having no data at all is probably not a common situation. In this situation, regional methods of some type are required. In addition to formal regional methods, parameters can be determined from experience with applications on similar systems or where the physical characteristics are similar.

b. *Very Limited Data* - The limited data may be some anecdotal records (Book 1, Chapter 4). An example for the design of drainage structures on a road or railway would be reports on the frequency of closure by flooding. In this case, it is possible to develop parameters that mean that the model is at least consistent with local observations. It may also be the case that the limited data is apparently inaccurate or inconsistent, though the exact source of this inaccuracy may be difficult to detect. In any case, efforts should be made to incorporate any information available in accordance with its assessed accuracy and reliability, no matter how limited this may be.

c. *Some Data* - In this case there may be a streamflow gauge with a very short period of record, records of flood levels for a single flood event or there may be records for a very frequent flood event. Some rainfall gauge information may be available. In this case, there will be a greater degree of confidence in the calibration, but the limited data means that there will still be uncertainty in the model performance, especially when the model is used for extrapolation to larger design events outside the range of the limited data or applied to alternative development scenarios.

d. *Extensive Data* - In this case, there is extensive data throughout the floodplain and catchment of interest. Data is available for a range of flood magnitudes and conditions and the flood data is accurate, reliable and consistent. In this case, the model calibration will be reliable and the model can be confidently used for design flood investigations.

These four categories blend together and there will be a gradation from one to the other. Projects where data is totally lacking are not common and projects with extensive data are also unusual. The objective is to consider all available data and to make the best use of all available information.

In the following sections the term *'calibration'* is applied to parameter estimation approaches c) and d), where the availability of flood data is sufficient to allow a calibration process that compares model results to observed flood data.

5.4.2. Types of Calibration Data

Types of calibration data are detailed in Book 1, Chapter 4 and include:

- Historical changes to topography, land-use, structures and drainage infrastructure;
- Records (photographs) of bed, bank and floodplain vegetation levels to assist with interpretation of roughness and provide record of prevailing conditions;
- Rainfall records (daily and pluviograph records), including in adjacent catchments;
- Gauged water level hydrographs, rating curves and derived flow hydrographs at streamflow gauge sites;
- Streamflow gauging at gauge sites and over the side of bridge structures (rare, but useful);
- Tidal level records if in a tidal area;
- Flood mark levels, location and measure of reliability. For example, debris marks, watermarks on/in buildings;
- Descriptive anecdotal information and past reports of flood behaviour in general;
- Observations of the rate of rise of flood waters and the time of peak;
- Photographs or videos of historical floods;
- Records or observations on water speeds and/or flow patterns;
- Records of blockage at hydraulic structures such as culverts and gully traps;
- Records and photography of the extent of inundation, noting the time of the photos; and

Information on road/railway closures.

> A flood occurred whilst calibrating a model. One of the local landowners phoned and asked if there was anything he could do? Make as many flood marks as you can, and if possible try to record when the marks were made. The local diligently went round hammering nails into trees until the flood peaked. After several weeks trying to calibrate to this fantastic data set, the practitioners were desperate, and visited the landowner. The model is always showing much higher levels than you've recorded. After a while the landowner took them over to the creek bank and showed them a levee hidden amongst the trees. Don't tell anyone he says, as I'm not sure if it's legal. In the end he agreed to have it surveyed, and lo and behold the model calibrated beautifully!

5.4.3. Anecdotal Information

While sourcing the observed flood data, it is important to also source descriptive or anecdotal information. This information can be just as valuable in the calibration process, especially where the observed data are scarce. Anecdotal information is best sourced through:

- *Discussions with Local Residents on their Recollections and Observations* - For example, they may have experienced a flood event and have noted features such as flow directions, water speeds and the timing of the flood's rise and fall. This information can be valuable to help check that the model's representation of flow behaviour is realistic; and
- *Information From Stakeholders* - For example, a road or railway authority may be able to advise how frequently a crossing is inundated and/or for how long. While this may not provide event specific observed data, it could be useful as to whether the model is in the right general area of performance.

> An old timer recalled how his grandfather remembered a large flood in the 1860s that broke across a ridge in two locations. Today, this would isolate the hospital and be a significant flood risk to homes. The 1% AEP flood did not show this flood behaviour, however, when the 0.2% AEP event was run, these floodways developed. This helped convince the old timer that the modelling was good, and the local council incorporated these floodways into their flood risk management planning.

> During a resident survey a local shop owner took the practitioner to look at a tree. "See that fork up there; well that was where a pig got stuck." Fortunately, the modelling for that event showed flooding to that height, and was proof to the local that the model was "doing the right thing".

5.4.4. Range of Flood Data

Calibration of flood models requires observed flood data (Book 1, Chapter 4) and generally data for several different flood events is needed. Application with data only from a single flood event means that there is less confidence in the calibration when extrapolating to design flood applications, especially considering that there may be errors in the data from the single event and this cannot be checked for consistency with others.

It is therefore desirable to have data for more than one flood event available for calibration, and hopefully several floods where a range of conditions is covered. Having floods of different magnitudes so that the flooding covers in-bank and floodplain flows and where flooding occurs in different seasons and with different rainfall distributions and catchment conditions will build confidence in the model performance. Successful calibration on a wide range of calibration events means that the model can be extrapolated to a wider range of design flood situations confidently.

5.4.5. Hydrologic and Hydraulic Models

The use of catchment modelling systems for design flood estimation generally involves two applications, namely the hydrologic and hydraulic components.

The hydrologic component, which is the model used to calculate flood peak discharges or flood hydrographs, is the more critical of the two, as any errors from hydrologic modelling will also transfer to the hydraulic modelling component. Calibration of the hydrologic model requires recorded flood flows, and these generally require a streamflow gauge. Availability of a streamflow gauge measuring discharges is less common than having flood level observations which may be provided by local residents and other non-experts. In some cases observed flood levels can be converted to flood flows by application of a stage-discharge relationship derived by a theoretical method (Book 1, Chapter 4), but this introduces another level of uncertainty into the calculation of discharge. The hydrologic model should be calibrated to ensure that the model can calculate flood flows to match the recordings. Calibration of hydrologic models must consider the accuracy of the recorded data and the consistency between different observations. These issues are discussed further below.

The hydraulic modelling process involves setting relevant parameters so that the modelled flood levels or flood hydrographs match the observed data. Observed flood levels are more commonly measured than flood discharges so there is often more extensive data. However, flood levels may be matched with a hydraulic model where the calculated discharges and hydraulic model parameters (primarily hydraulic roughness) are both incorrect and the errors compensate. While this is not necessarily a problem for the actual historical flood used for calibration, this can lead to significant errors when using the model for design applications over a larger range of flood events.

In many cases though, the hydrologic and hydraulic models may be calibrated together, ie. Joint calibration. In this situation, there may be observed flood levels but no recorded discharges, and the parameters for both the hydrologic and hydraulic models are adjusted together and the discharge determined such that the final flood levels are matched. As with the calibration of hydraulic models, this situation may lead to compensating errors in the two models, and the calibration may appear reasonable but the compensating errors mean that flood estimation for floods of different magnitude may be significantly in error. The compensating errors mean that the flood discharge is too low and the roughness is too high and the flood levels match, or the opposite.

5.4.6. Selection of Calibration Events

Prior to collecting and analysing all data for a calibration exercise, suitable historic events need to be identified and selected. The practitioner should primarily consider the:

- Amount, type and quality of suitable data available for each event; and
- Magnitudes of the events as to whether they are of a similar size to that of the primary design events.

Each calibration event must have sufficient historic flood observation and reliable topographic information and boundary data at the time of the flood. Often this means that events used for calibration are relatively recent, as the data sets are likely to be more complete. Larger floods that may have occurred longer ago may not be suitable for calibrating to due to the lack or scarcity of key data sets.

Calibration events should ideally also span the magnitude range of the intended design events with a preference for the more important design floods (e.g. 1% Annual Exceedance Probability event). This instils confidence in the ability of the model to replicate flow behaviour over the full range of event magnitudes. For example, a frequent flow event that is confined to the channel and drainage infrastructure will have a substantially different behaviour to a rare flood event that has broken the banks and is flowing overland. If the model has only been calibrated to the in-bank flow magnitude, confidence in its ability to replicate overland flow will be lower.

For tidal sections of a flood model, a tidal calibration is a useful additional calibration step, and is particularly recommended where storm tide inundation and interaction with catchment flooding is important. Tidal calibration data often exists, or can be readily measured, and is usually an accurate data set. It also provides a check that the model can reproduce any tidal amplification.

> The 1998 flood in Katherine was larger than a 1% AEP event. There were extensive water level measurements taken throughout the town, many photographs and videos and the flood discharge was gauged at the gauging station. Therefore, the data available for calibration at Katherine for this event could be regarded as ideal: a large recent event with a reliable and extensive dataset.

5.4.7. Calibration Processes

The calibration process for flood models involves the adjustment of model parameters so that the model results match the recorded data. This process can proceed in one of several ways, though often a combination of different approaches is most effective.

When there is good quality data, there are automatic calibration algorithms that follow a defined search procedure to result in an “optimum” parameter set. While in theory, this procedure can result in a good quality parameter set with a minimum of effort, this approach is not as straightforward as first impressions indicate. The first step is to define an objective function that must be minimised for the optimisation. This may be minimising the root mean square error for the differences between observed and modelled flows. While this function may lead to a generally overall reasonable result, it may be more important to concentrate on high flows for example (a common requirement for flood studies), the rising limb of flood hydrographs (required for flood forecasting) or hydrograph volumes and shape (commonly needed for floodplains with extensive floodplain storage). These secondary details are often equally important and it is generally found that a purely automatic optimisation procedure does not converge to the optimum parameter set for a particular application, unless the objective function of the optimisation procedure has been carefully chosen.

Automatic parameter optimisation routines do not necessarily include an understanding of model processes and, if the objective function is not well selected, the optimisation may not represent the particular model application and produce realistic parameters. Manual parameter optimisation is the situation where the practitioner can vary model parameters based on the results of earlier model runs to progressively adjust model performance, and to incorporate an understanding of the model and catchment processes and the required model application.

Automatic optimisation procedures provide an approach for parameter estimation that in some situations can result in a good fit to the calibration data. However, in large and complex models there are usually many parameters, some of which only influence the model performance in particular circumstances. These automatic procedures may result in unrealistic parameter values and the performance outside the calibration range depends to a large extent on the objective function chosen for optimisation. Many objective functions will focus on the rarer floods while baseflow and frequent floods are poorly represented. These other details of the streamflow pattern are often important and it is difficult to find an objective function that can operate for all of the different conditions that may be needed.

Because of this, the most appropriate means of model parameter estimation should involve both automatic and manual parameter estimation where the modeller uses experience and understanding to estimate parameters appropriate for the particular application and the automatic procedures can refine and polish the optimisation.

Calibration, especially for large and complex models, may require a long process and tests on a large number of parameter combinations and variations. In this situation (which is common, except for the most simple situations) it is important that the practitioner maintains a log of calibration tests so that the impact of parameter changes can be understood and the calibration can proceed without retracing previous calibration tests.

5.4.8. Objective Function for Calibration

When a hydrologic or hydraulic model is being calibrated, the objective is to match the model results to observed data, but there are different ways of measuring the quality of the model fit.

A common application is to fit the model results to observed flood levels or flood hydrographs. Obviously, the objective is to fit the observations as closely as possible. However, the model will often show that it is over-estimating for some points and under-estimating for others or one flood may be consistently over-estimated while another is consistently under-estimated.

The aim therefore should be to provide the best “overall” match, though this is hard to define. Points to consider are that there should not be any consistent error, there should be some recorded points above the model results and some below and points of lower accuracy should not be weighted as heavily as those regarded of high accuracy. Estimates of rare design floods are most often required for flood studies, so the optimisation should normally be weighted towards the larger calibration events.

In most situations, flood peak levels are the most important objective, but in some cases, the hydrograph shape or flood volume may be of as much significance as the flood peak levels, so the model application must be considered when deciding on the objective function.

The objective function may be a mathematical parameter, such as minimising the sum of squares of the errors, or the function may be based more simply on fitting “by eye”, where judgement can be used to determine the quality of fit for different features of the observed flood record. There is a place for both of these approaches, even in a single application.

The calibration is assisted when the practitioner has a good understanding of the model processes and the influence of all parameters in the model. Knowledge of which parameters are most influential, and the influence of each parameter on different aspects of the flood process, is important in ensuring that the model parameters are maintained with realistic values and that efforts are not wasted working on insensitive parameters. Models with multiple parameters will usually exhibit interaction between the parameters so that it is possible that a similar calibration performance is achieved with different parameter sets. With incorrect parameter combinations, while the calibration performance may be similar, there are likely to be major differences in the design application results when the model is applied to conditions outside the range used for calibration. It is important therefore to have an understanding of the model operation and the relationship between parameters and physical characteristics to help keep parameters within reasonable bounds, especially when considering interactions between parameters.

Therefore a single objective function cannot be recommended for all model calibrations, a variety of methods will be applicable for particular applications.

5.5. Data Issues

5.5.1. Overview

When calibrating models for flood analysis, the first point is the assessment of the available data. Clearly maximising the quantity of data used for calibration will be a priority. However the data should be accurate and consistent or the calibration process may be impossible or it may lead to an incorrect model application and the catchment modelling system will be impossible to apply in practice. It is important to be aware that the flood estimation models need to be applied to practical problems, and the focus of model calibration is not just the preparation of a model that is well calibrated to the available flood data. Application of the model to the design requirements must be the primary focus, and the calibration must be prepared to the extent needed to have confidence in the design application.

While it is important to critically review the quality of the data available for calibration, it is also important to carefully review all available data and maximise the information available in this data to ensure the best possible calibration process. Formal data collection programmes are an immediately obvious source, but all available information should be examined. For example, old historic records from newspapers may be available to give an indication of major historic floods from before official records are available. These old records though do need careful study, since the survey datum may be hard to identify but some “detective” work can yield valuable information.

Careful review of the quality and properties of the data being applied for calibration is essential to ensure that it is appropriate and that the practitioner has a good understanding of the availability and applicability of the data. This is especially important for older historic data. Issues can include:

- The datum used for level survey where older data may use a different datum or two sets of survey data may be to two different datums;
- Streamflow gauge records of water levels are often measured to a local datum, which may be difficult to relate to topographic data;
- Stream channels may scour or silt up over time so current conditions may be different from those when the flood records were collected; and
- Floodplain roughness may vary with time, for example, sugar cane fields may be bare ground or very dense sugar cane depending on the time of year when the flood occurs.

Many types of informal data collection can assist in ensuring that model calibration is as accurate as possible, and these are discussed in Book 1, Chapter 4, where the value of data in all types of flood estimation is identified.

5.5.2. Changes to Catchment Conditions

The catchment condition data used in a model platform is typically that of the current day. This is due to the fact that an airborne and infrastructure survey is usually undertaken close to study commencement. In using this current day dataset, there are a number of potential calibration issues that the practitioner needs to consider.

As described in Book 1, Chapter 4, catchment conditions at each of the relevant historic calibration/verification periods must be established and used in the model. Changes to conditions that may affect flood behaviour include:

- dam construction;
- changes to initial dam storage levels and/or operations;
- dredging or siltation of river entrances;
- levee construction or raising;
- road/railway raising or duplication;
- new road/railway embankments;
- new culverts or bridges;
- upgraded drainage networks;
- development on the floodplain;
- different crop types or growth stage;
- changes in stream bed and bank profiles; and

changes to vegetation including seasonal variations.

> The last major river flood in one coastal area occurred in 1974 and resulted in extensive inundation of the floodplains. At this time, the floodplain was mostly utilised as grazing land. That land is now developed with extensive canal and flood mitigation works. While model calibrations for these rivers must rely on data from the 1974 flood, the drastically changed conditions mean that calibration results must be treated with appropriate caution.

> A 2D model was constantly producing flood levels that were too low in the upper tidal reaches of one branch of a coastal river. However, modelled flood levels matched recorded well in all other locations. Not even extremely high Manning's n values would lift modelled levels to those recorded. It was initially suspected that the recorded levels were erroneous, but this was proved incorrect when the recorded flood levels were independently resurveyed and found to be accurate. It was later revealed by a long term resident that a weir that had been installed to prevent saline water penetrating upstream, had never been completely removed and was still controlling flows. Once this partial weir was included in the model, a good fit was obtained with the same parameters used elsewhere in the model.

5.6. Acceptance of Calibration

When calibrating model parameters an important decision is to determine when the calibration is acceptable and when further refinement cannot be justified. There is often a temptation to continue to refine model parameters beyond what can be justified by the available data, which may be a lengthy process that does not lead to any improved performance in model application.

It is far more important to understand why a model may not be calibrating well at a particular location than to use unrealistic parameter values to ‘force’ the model to calibrate.

Considerations in the decision on when calibration can be accepted are:

- *Accuracy of Calibration Data* - The quality of calibration will depend on the assessed accuracy of the calibration data (refer to section on Data Issues above). For example, if the calibration of a hydraulic model is based on flood levels from observed debris marks, these levels may not be more accurate than ± 300 mm, so working towards matching a number of levels to a higher level of accuracy cannot be justified. Even where there is a streamflow gauge located on the catchment, the quality of the measured discharge will depend on the quality of the rating curve, which could cause quite significant inaccuracy in this measured data.

- *Representativeness of Calibration Data* - Calibration data may not be representative of the floods required for application of the model. For example, it is often the case that calibration floods are relatively frequent while design applications require much rarer floods. In this case, the value of refining the model calibration extensively to the frequent floods cannot be justified, since the significant extrapolation of the model means that the parameters may not be justified.

- *Number of Calibration Events* - The quality of calibration depends on the representativeness of the data and an important factor in this area is the number and range of events with suitable calibration data. In some cases, there may be only a single frequent flood event available for calibration and in this case, the quality of calibration will be poor especially where the model must be extrapolated to rare design events. When a model can be calibrated to several different flood events of a range of sizes and covering a range of different conditions (such as rainfall distribution or season), the resulting model can be applied with much more confidence than is possible where the data is limited.

- *Model Response and Catchment Consistency* - The calibration of models relies on the available data and the estimated parameters are based on the data used to estimate the parameters. However, the catchment conditions that applied during model calibration, especially if rare historic floods have occurred, may not be completely representative of conditions required for design applications. Because of this the model parameters required for design should be “generic” parameters based on the calibration but applicable for the design application. The exact catchment conditions for design applications may not be consistent with the particular conditions that applied for the calibration process. For example, vegetation coverage on a floodplain or the channel conditions in water courses will vary from time to time, so the conditions that applied for a single calibration flood event may not be representative of long term average conditions. Parameter values therefore must be modified to account for the expected future design conditions, rather than an unrepresentative calibration event.

- *Consistency of Data* - Review of data may indicate that the recorded data is inconsistent. For example, recorded flood levels for two different floods may be impossible to model with the same parameter set. There are several possible reasons for this possibility. For example, the recordings may be inaccurate, the catchment or floodplain may have changed between flood events or the model may be inappropriate for the analysis required. The effort should then be concentrated on resolving the source of the inconsistency rather than pursuing further calibration.

- *Requirements for Model* - The calibration acceptance may vary depending on the application required. For example, if the model is required for a bridge design, the calibration is only really critical for the bridge site, but model performance over a wider extent of the catchment is needed for floodplain planning. Also if the model is required for assessment of frequent floods, the performance for major overbank flooding is not as relevant so poor performance for these events is not a serious concern.

- *"Overfitting"* - This is the process where the model calibration process is taken to an extreme, and the model parameters are extended to possibly unrealistic values and can vary unrealistically throughout a catchment or floodplain to ensure that the model fit is close for all data points and all events. This situation may result when there are unrealistic calibration acceptance criteria adopted for the project and the only way of meeting the criteria is by an extreme and unrealistic parameter set. While the resulting model calibration may appear to be high quality and does meet calibration performance criteria, the resulting model parameters will not improve the performance of the model for extrapolation to the design situation.

It is extremely rare that a flood model will fit all data well. This usually means one of the following:

1. The model has been overfitted to the data with unrealistic parameter values; and

2. Some of the data that does not fit well, has been ignored and not presented.

It is extremely unlikely that your simple model is perfectly representing the complex real world well, all your data has been collected without error, or is unaffected by local factors.

For these reasons, it is difficult to define an acceptance criterion for model calibration and the quality of calibration may vary depending on particular conditions. It is important though to consider all the issues covered here when deciding on calibration performance. Unrealistic calibration criteria do not lead to an improvement in model design applications so the criteria need to be tailored for the particular application and local situation.

The quality of calibration depends on the quality of the data applied so the model application and results should consider this in interpretations of model results.

It is recommended that specifications for flood studies should not be prescriptive in defining calibration criteria, but should aim for realistic and applicable criteria.

It is important to note that a calibration process may not always result in a parameter set that is suitable for application to design conditions, and it is always necessary to approach calibration data critically. In these cases, the calibration process must be supplemented with other information such as regional parameter estimates as discussed in Book 7, Chapter 6.

Sensitivity testing of inputs and parameter values is a good way of understanding and resolving the importance of the input/parameter on the model's calibration results. This is discussed further in Book 7, Chapter 7.

Following a large flood event that occurred in 1984, Council organised the survey of over 400 peak flood marks across the floodplains of the affected catchment. These were primarily flood debris marks. Prior to model calibration, Council specified that the calibration criteria was for modelled peak water levels to be within 300mm of recorded. However, calibration was accepted with 50% of points meeting this criterion in recognition of significant proven uncertainties in debris mark levels and some of the model inputs.

When calibrating a model to peak flood levels for one historic event, a good match between modelled and observed was obtained for all levels with the exception of the one recorded by the most upstream automatic gauge. The datum of the offending gauge was checked and no problem was found. In order to match this gauge, Manning's n values needed to be set at values that were outside the normal range and very different to elsewhere in the model. In addition, the peak level at this gauge looked out of place on a longitudinal plot of the river profile. Despite a strong desire to have the model calibrate well to this one gauge level, the client accepted the practitioner’s advice that confidence in the accuracy of the observed level was low and it would be compromising the model to fit the data. Not long after the study was complete, a larger flood occurred and the model fitted all gauge data very well, including the troublesome gauge. It was concluded that something had gone wrong with the automatic gauge in the earlier event.

5.6.1. Matching Timing and Magnitude

Ideally, a model is calibrated to observed water level marks and hydrographs. Observed marks are usually at the flood peak and often spread throughout the model domain. Calibrating to these marks shows that the model is capable of reproducing the peak water level distribution. However, especially if the model only covers a small extent of the overall river/creek system, this does not necessarily mean that the model is well calibrated.

Also, fundamental to a good calibration is the demonstration that the model reproduces the timing of flood events. This may be achieved through calibrating to recorded water level hydrographs (if available), and to observations by locals (e.g. “the flood peaked around midday”). Water level hydrographs give the added benefit of showing whether a model is reproducing the shape (rise and fall) of the flood.

Calibrating to information on the timing of the flood shows that the flood dynamics are being reproduced, and this only occurs if the model’s input data and schematisation are satisfactory, parameter values are within typical ranges, the software is suited to the application, and most importantly, the hydrologic method is also reproducing the correct timing. The latter is particularly important when it comes to calibrating a hydraulic model. If the hydrologic method is inaccurate with respect to timing and/or magnitude, satisfactory calibration of the hydraulic model will be difficult, if not impossible. For this reason, jointly calibrating the hydrologic and hydraulic modelling is always recommended.

If parameters such as hydraulic roughness are outside standard values, the calibration may be “acceptable” for that particular event, but will very likely be compensating for inaccuracies in the hydrologic modelling, input data and model schematisation. In this case, the “calibrated” model is not suited to representing floods of smaller or larger size than the calibration event, and will be of limited use.

It is important to note that should flow/discharge hydrographs exist for a study area, the flows are not “recorded” but “derived”. A rating curve is used to convert the water levels recorded by the stream gauge into flows. Details on this process and its limitations are provided in Book 1, Chapter 4. However, it is worth reiterating that the reliability of discharge data is limited by the number and quality of manual gaugings undertaken at the site, the extent of extrapolation beyond the highest gauging of the rating curve and the means by which the rating curve is developed by the hydrographer. In undertaking a calibration using flow discharge hydrographs, it is essential to consider the quality and reliability of the rating curve used to derive the flows. Inaccurate rating curves produce inaccurate flows that will potentially mislead the practitioner into using inappropriate parameter values.

5.7. Ungauged Catchments

The model calibration processes discussed in this chapter apply when there is data (of varying levels of completeness and accuracy) to assist in the calibration. However in many cases, if not most, calibration data is either totally lacking or limited to sparse anecdotal information on flooding. The term ‘ungauged catchment’ here is meant to include also flooding areas with no or only very limited flood level observations. In these situations, the model parameters must be estimated to the best degree possible using what information is available. In these cases, while a complete calibration procedure is not possible, the model parameters can be estimated to some extent by other means, though there will obviously be additional uncertainty compared to the situation when there is adequate calibration data.

While many applications are required on totally ungauged catchments, it is common to have at least some minimal records of flooding available. The minimal descriptive data availability is discussed further in Book 1, Chapter 4, but where there is some anecdotal data, the parameter determination process must use this data to at least ensure that the model performance is consistent with this minimal data even if the data is insufficient to provide a calibration.

An important issue with the estimation of parameters for ungauged catchments is that the methods rely on transfer of parameter values from neighbouring catchments. The methods therefore rely on the assumption that the catchments used to estimate parameters are sufficiently similar to the catchment being analysed. It is important to carry out as many checks as possible to confirm that this is the case, but there will always be some uncertainty.

There are several different methods of estimating model parameters for ungauged catchments.

- *General Guidance* - Published documentation, including user guides for particular modelling platforms as well as textbooks and research publications, provide guidance for estimating parameters for ungauged catchments. These include advice on Manning’s n values for example which is widely available in textbooks and manuals. However many modelling platforms provide general guidance and in some cases, user forums can be of assistance.

- *Regional Relationships* - These are developed for particular model parameters and for particular regions. For example, there are published relationships for runoff-routing parameters which are related to catchment area, for several regions of Australia. In some cases, specific regional relationships are developed for particular project areas from limited data and then adopted for the whole project area.

- *Transfer from Neighbouring Catchments* - This is a special case of the regional relationship type approach. If the catchment being analysed is not gauged but there is a neighbouring gauged catchment that has similar characteristics, it is possible to calibrate a model on the neighbouring catchment and then transfer the parameters across perhaps with adjustments for the known differences, such as catchment area. There is a risk in this case that the neighbouring catchment may appear superficially similar, but may have a quite different catchment response.

The principal issue with parameter estimation for ungauged catchments is to use whatever data may be available, no matter how poor quality this may be, understand the physical processes represented by the models to ensure that the parameters are realistic, and to use regional relationships and information from neighbouring catchments to the maximum extent possible. The uncertainty in the resulting model operation must be considered in any model application for ungauged catchments, since this will be greater than would be the case for a well gauged catchment.

5.8. Adopted Parameter Set

The ultimate requirement for model parameter determination is to apply the calibrated model to certain design situations, as discussed further in Book 8. However some comments are provided here to give advice on the final step of the calibration process where the parameters resulting from the calibration process and from other sources of parameter estimates are accepted and reviewed further in a validation process (Book 7, Chapter 7) and then applied to design.

Often the calibration process will result in different parameter sets applying for different calibration events.

In general, this is not allowable, since a single parameter set will be required for application so after completing calibration on a number of different flood events, the calibration process must continue to calculate a single parameter set to best fit all of the available data. Therefore a procedure is needed to select a representative parameter set for application to the design situation.

The simplest approach would be to “average” the parameters, which will result in parameters that are representative, but may not result in a model that “averages” performance. An alternative approach to simple averaging would be to average them with a weighting towards the rarer floods. It is also possible to adopt the parameter set that has been estimated from the historic flood that is most similar to the design flood requirements, which may be the largest flood event.

Whichever technique is adopted to interpret the calibration results and adopt parameters for a design application, these adopted parameters should then be used with the model on all of the design flood events to confirm the performance for all the data. The results from this should show at least a reasonable performance for all of the calibration flood events and no bias in the results, that is the calibration on all historic floods should not be all under- or over-estimations.

It is desirable to compare the adopted parameter set from the calibration events with parameter estimates from catchments and flooding areas with similar characteristics and with parameter values obtained from regional parameter estimation procedures. If there are any significant discrepancies between the parameter estimates from different sources, the possible reasons should be investigated and the final parameter selection decision made in the light of the findings from these considerations.

Once the calibration has been accepted, the model should then be transferred to the validation phase, where the parameters are confirmed and determined to be available for application.

Chapter 6. Regional Relationship for Runoff-routing Models

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6.1. Introduction

Regional relationships can be used to estimate parameter values on ungauged catchments but they can also be used to test the plausibility of parameters derived from limited data. Where no data is available some insight can also be gained from comparing how adjoining catchments with data compare to the regional relationship. Relationships between model parameters and catchment characteristics have been derived for several regions. The most recent relationships available for Australia are given in the following section.

In all cases the reliability of regional relationships is likely to be less than parameter estimates derived from calibration from several recorded flood events on the catchment of interest. Regional relationships should be used with due caution, as most derived relations incorporate considerable scatter of the data from individual catchments. Also, different forms of relationships have been found to give equally good fits to the one set of data, but would give widely different estimates in some other cases (Sobinoff et al., 1983).

6.2. Regional Relationships

The following relationships for RORB and WBNM apply to catchments in natural condition. Regional data for RAFTS and URBS are not as extensive as for the other two models, and suggested parameter values for these models are included in Book 7, Chapter 5.

Regional relationships will contain some scatter about the fitted equation, partly due errors in rainfall and streamflow data, including insufficient spatial rainfall gauge coverage, but also due to limitations in the models themselves. Loy and Pilgrim (1989) quote typical errors of 10-20% for rainfall and 25% for streamflow data, with larger errors being quite possible, and note that as a consequence high correlation is unlikely to be obtained in the resulting regional relationships.

Scatter in the relationships can also be caused by different methods of treating the data when parameters were originally calibrated. These include different assumptions when separating baseflow, and different rainfall loss models, for example proportional loss as opposed to continuing loss rate. These different assumptions can lead to different calibrated parameter values, and hence contribute to scatter in the regional relationship. This problem will be reduced if the regional relationship is developed using consistent methods of treating the data. However, when parameters are combined from several different studies to develop a regional relationship, care should be taken to ensure that consistent parameter values are used.

Another cause of scatter can result from different parameters being derived from calibrations using floods of different magnitudes. Wong (1989) found that calibrated values of the RORB parameter k_c were larger for larger floods, when overbank flow became established, compared to smaller in-bank flows. Similar effects are likely in all runoff-routing models. The use of a single catchment parameter value in regional relationships, without regard to the magnitude of the flood, may therefore call into question the validity of the relationship (Wong, 1989).

It is important to note that that the value of the lag parameter *k* (Book 5, Chapter 5, Section 4) (or the corresponding k_c, C, B and β parameters in RORB, WBNM, RAFTS and URBS respectively) depends on the values of other parameters adopted during calibration of the model. The values of these lag parameters used in regional relationships will be dependent on the values of, for example, the nonlinearity parameter *m*, as well as the stream channel routing method used and the stream channel parameter values adopted. Another cause of variation in the lag parameter can occur if the basic model is modified, for example by allocating proportionally greater lag time to subareas and less to stream reaches (Kneen, 1982) in which case the calibrated *k* values will not be consistent with those calibrated for the same events using the basic model.

It is possible to obtain an approximate adjustment for *k* (or K_c, C, B or β) values which have been derived using other values of *m* so that they correspond to a base value, for example, *m* = 0.8 (Morris, 1982). This is done by adjusting *k* so that the same overall lag time K is maintained for the different *m* values, using Equation (7.6.1). This requires an average or representative discharge for the particular flood, which will be half or less than half of the peak discharge Q_p. Pilgrim (1987) used an average discharge equal to $Q_p/2$, giving the following adjustment:

$$k_{0.8} = k_m \left(\frac{Q_p}{2} \right)^{m - 0.8} \tag{7.6.1}$$

where k_m is the lag parameter (K_c, C, B or β) corresponding to a specified value of *m*.

Most regional relationships relate the lag parameter to one or more physical characteristics of the catchment. These are most commonly the area A, stream length L and stream slope S_c, although other measures, such as elevation, average rainfall and drainage density are sometimes used. Different studies sometimes use different definitions of stream slope S_c so that caution is needed to ensure that the correct definition is used when applying the relationships. Measurements of stream length L are dependent on the map scale used (Cordery et al., 1981) and this should also be considered when applying the relationships. Stream length is strongly correlated with catchment area and stream slope is moderately correlated with area, so that relationships involving area A alone, or stream length L alone are often sufficient to describe the regional relationship.

6.2.1. Regional relationships for RORB

The greatest number of derived parameter values and regional relationships are available for the RORB Model. The relationships recommended below are derived from all readily available data. Values of the parameters and the catchments used in deriving the relationships are generally listed in the cited publications. Although the nonlinearity parameter *m* can be varied to improve the hydrograph fit when calibrating the model, most studies have found *m* to lie in the range 0.6 to 1.0, and many studies adopt a constant value of *m* = 0.8 (Hansen et al., 1986; Dyer et al., 1993; Dyer et al., 1995; Pearse et al., 2002). All relationships for k_c given in this section are for a value of *m* = 0.8 except where specifically noted.

Most of the relationships are of similar form and involve only the single catchment variable, area A in km^2, since this has been found to be the dominant variable. To allow comparisons, relationships developed by various researchers are presented, together with the number and size range of the catchments used (where available). The recommended regional relationships for each region are then given in boxes.

6.2.1.1. Queensland

Relationships have been developed by Weeks and Stewart (1978), Morris (1982), Hairsine et al (1983), Weeks (1986) and Titmarsh and Cordery (1991). For 14 catchments (158 to 3430 km^2) generally covering the coast, plus one catchment near Mt. Isa, Weeks and Stewart (1978) obtained:

$$k_c = 0.69A^{0.63} \quad (7.6.2)$$

$$\mathrm{m} = 0.73 \quad (7.6.3)$$

For 25 catchments (56 to 5170 km^2), with parameters adjusted to m = 0.75, Morris (1982) obtained:

$$K_c = 0.35A^{0.71} \quad (7.6.4)$$

For four catchments in the Darling Downs (2.5 to 50 km^2) with m = 0.8, Hairsine et al (1983) obtained:

$$K_c = 0.80A^{0.62} \quad (7.6.5)$$

For nine small catchments in south-east Queensland (0.002 to 50 km^2) with m = 0.8, Titmarsh and Cordery (1991) obtained:

$$K_c = 0.83A^{0.35} \quad (7.6.6)$$

For 88 catchments (2.5 to 16,400 km^2), covering both coastal and inland areas of Queensland, with parameters adjusted to m = 0.80, Weeks (1986) obtained:

$$K_c = 0.88A^{0.53} \quad (7.6.7)$$

Although Equation (7.6.2) to Equation (7.6.8) appear to be quite different, when plotted together, with each relationship covering its range of catchment sizes, they conform to a general trend and can be viewed as different samples from the population of Queensland catchments. The relationship of Weeks (1986), equation Equation (7.6.8), is a good average to all relationships and is recommended. Weeks (1986) also investigated possible variations of K_c within the various regions of the study, and also any effects of catchment slope, but no relationships were found.

The relationship of Weeks (1986), Equation (7.6.8), is a good average to all relationships and is recommended.

$$K_c = 0.88A^{0.53} \quad (7.6.8)$$

6.2.1.2. New South Wales

Relationships have been developed by Kleemola (1987), Sobinoff et al. (1983) and Walsh and Pilgrim (1993). For 26 catchments (0.1 to 4560 km^2) in the Newcastle-Sydney-Wollongong region, with m = 0.8, Sobinoff et al. (1983) obtained:

$$K_c = 1.09A^{0.45} \tag{7.6.9}$$

No regional trends were apparent, except for some lower values of K_c in the Upper Hunter valley. Addition of slope to the regressions did not improve the fitted relationships appreciably. Walsh and Pilgrim (1993) added to the data of Kleemola (1987) and derived relationships for 46 catchments (0.1 to 13,000 km^2). Relationships were derived using area A, stream length L and stream length divided by slope (L/S$^{0.5}$). The fit of these various relationships to the data were similar, and a relationship involving area A was considered to be the most logical one to adopt. The relationships were:

West of Great Dividing Range, upper western slopes and tablelands (12 catchments, 100 to 4770 km^2)

$$K_c = 0.80A^{0.51} \tag{7.6.10}$$

East of Great Dividing Range (34 catchments, 0.1 to 6465 km^2)

$$K_c = 1.18A^{0.47} \tag{7.6.11}$$

Since the relationships are very similar, a combined relationship was derived for all 46 catchments:

NSW catchments

$$K_c = 1.18A^{0.46} \tag{7.6.12}$$

Walsh and Pilgrim (1993) found that most catchments had values of m in the range 0.75 to 1.0 and adopted a fixed value of m = 0.8 for all catchments. No trends for K_c to vary with event size were evident, indicating that the nonlinearity was adequately described by adopting m = 0.8. Weighted average and direct average K_c values were calculated from all events on each catchment, with little difference being apparent.

When Equation (7.6.9) to Equation (7.6.12) are plotted to cover their range of catchment sizes, all equations are very similar, and equationEquation (7.6.12) is recommended for catchments both east and west of the Great Dividing Range.

Equation (7.6.13) is recommended for catchments both east and west of the Great Dividing Range.

NSW catchments

$$K_c = 1.18A^{0.46} \tag{7.6.13}$$

6.2.1.3. Victoria

Regional relationships have been developed by Morris (1982) and Hansen et al. (1986).

Morris (1982) developed relationships for 16 catchments (20 to 1924 km^2) with m = 0.75:

$$K_c = 1.37A^{0.59} \quad (7.6.14)$$

Region with mean annual rainfall greater than 800 mm (19 catchments, 38 to 3910 km^2, mainly the eastern part of Victoria):

$$K_c = 2.57A^{0.45} \quad (7.6.15)$$

Region with mean annual rainfall less than 800 mm (21 catchments, 20 to 1924 km^2, mainly the western part of Victoria):

$$K_c = 0.49A^{0.65} \quad (7.6.16)$$

The relationships of Morris (1982) and Hansen et al. (1986) for RF > 800 mm are reasonably consistent, while the K_c values for the drier part of the state are somewhat lower, particularly for the smaller catchments. Comparing the Hansen et al. (1986) relationships for the eastern and western parts of Victoria, predicted K_c values are similar for catchments greater than about 2,000 km^2, but the eastern region values are approximately double for catchment areas near to 100 km^2.

6.2.1.4. South Australia

Regional relationships have been developed by Lipp (Pilgrim, 1987), Maguire et al. (1986) and Kemp (1993). For the south-east region, corresponding to zone 6 of the ARR design storm temporal patterns, Australian Rainfall and Runoff (Pilgrim, 1987) recommended:

For catchments smaller than 100 km^2:

$$K_c = 0.60A^{0.67} \quad (7.6.17)$$

For catchments larger than 100 km^2, based on limited data:

$$K_c = 1.09A^{0.51} \quad (7.6.18)$$

For the northern and western regions, corresponding to zone 5 of the ARR design storm temporal patterns, Australian Rainfall and Runoff (Pilgrim, 1987) recommended for flat to undulating country:

$$K_c = \text{Coeff.}A^{0.57} \quad (7.6.19)$$

where the Coefficient ranges from 1.2 to 1.7 for equal area stream slopes ranging from 1.0 to 0.2%.

For the northern and western regions, undulating to steep country, with slopes greater than 1%, (Equation (7.6.25)) for the wheatbelt, north-west and Kimberley regions of Western Australia was recommended by ARR 1987 (Pilgrim, 1987). However, the more recent relations developed by Kemp (1993) are now recommended for these arid regions.

Kemp (1993) derived relationships for low and high rainfall areas, using m = 0.8. For average annual rainfall RF less than 320 mm (7 catchments, 170 to 6020 km^2):

$$K_c = 7.06A^{0.71} \quad (\mathrm{RF}/1000)^{2.79} \tag{7.6.20}$$

For average annual rainfall greater than 500 mm (17 catchments, 5 to 690 km^2):

$$K_c = 0.89A^{0.55} \tag{7.6.21}$$

For the higher rainfall south-east region, near Adelaide, There is a good agreement between Equation (7.6.17), Equation (7.6.18) and Equation (7.6.21). Equation (7.6.20) for areas with annual rainfall less than 320 mm also agrees with these equations for RF near to 320, the top of the applicable range. For the drier interior of the state, Equation (7.6.19) predicts higher K_c values, while Equation (7.6.20) predicts lower K_c values. Since the Kemp (1993) study is the most extensive, Equation (7.6.20) and Equation (7.6.21) are recommended for South Australia, but with the note that Equation (7.6.20) predicts quite low K_c values for the drier interior of the state.

6.2.1.5. Western Australia

Regional relationships have been developed by Weeks and Stewart (1978), Morris (1982), Flavell et al. (1983). Netchaef et al. (1985) present some data for the Pilbara region. For 6 catchments in the southwest (67 to 805 km^2), Weeks and Stewart (1978) derived:

$$K_c = 1.23A^{0.91} \tag{7.6.22}$$

The nonlinearity parameter *m* was also calibrated on each catchment, overall being near to *m* = 0.75. K_c values for western Australia were found to be considerably higher than for the eastern states, which they attributed to the observed more sluggish response to rainfall of these catchments. Morris (1982) for 24 catchments (28 to 5950 km^2), using *m* = 0.80 derived:

$$K_c = 2.48A^{0.47} \tag{7.6.23}$$

Flavell et al. (1983) derived relationships for 52 catchments (5 to 6526 km^2) in 4 regions of the state. A non-linearity parameter of *m* = 0.8 was found to give best results for the south-west, and was adopted for the entire state. Variables used in the regressions were catchment area A, main stream length L, main stream equal area slope S_e (m/km), and percentage of land cleared. Generally, regressions involving stream length L were better than those using area A. For the south west (26 catchments, 29 to 3870 km^2) relations for sub regions with different soil types were similar.

The following equation is recommended for all jarrah forest catchments in the south west:

$$K_c = 1.49L^{0.91} \quad (7.6.24)$$

Relationships for the wheatbelt, north-west, and Kimberley regions were similar and the following is recommended, based on 26 catchments (5 to 6526 km^2) :

$$K_c = 1.06L^{0.87} \quad S_e^{-0.46} \quad (7.6.25)$$

For the arid interior of Western Australia, Equation (7.6.25) is recommended.

L was converted to A through the relationship established by Boyd and Bodhinayake (2005) to allow Equation (7.6.24) and Equation (7.6.25)to be plotted against catchment area A. The relationships of Morris (1982) and Flavell et al. (1983) for the south west region are very similar and Equation (7.6.24) is recommended. Equation (7.6.25) for the wheatbelt, north-west and arid regions predicts K_c values which are considerably lower than for the south-west region. The earlier relation of Weeks and Stewart (1978) was based on only sixcatchments and predicts K_c values which are considerably higher than those of Flavell et al. (1983), and is not recommended.

6.2.1.6. Northern Territory

Relationships for K_c have been derived for the northern half of the Northern Territory by the Department of Mines and Energy (Pilgrim, 1987). The Northern Territory was divided into the three zones.

For the humid zone, north of latitude 15° S, with equal area slope S_e in m/km the following equation is recommended:

$$K_c = 1.8(A/S_e^{0.5})^{0.55} \quad (7.6.26)$$

For the transition zone, between latitudes 15° S and 17.5° S:

$$K_c = 0.35A^{0.64} \quad (7.6.27)$$

Equation (7.6.26) and Equation (7.6.27) are similar for catchments greater than 2500 km^2, but with smaller K_c values predicted for smaller catchments in the transition zone compared to the humid zone.

For the arid zone, below latitude 17.5° S ARR 1987 (Pilgrim, 1987) recommended the relationship for the northern and western regions of South Australia (Equation (7.6.19)) be used. Equation (7.6.19) predicts higher K_c values than both the humid and transition zones, and as discussed below, is not recommended. Equation (7.6.25), for the wheatbelt, north-west, Kimberley and arid interior of Western Australia, lies within the range of values for the drier interior of south Australia (Equation (7.6.20)) and is close to K_c values derived by Board et al. (1989) for two catchments in the arid zone near to Alice Springs.

Therefore Equation (7.6.25) is recommended for the arid interior of the Northern territory.

6.2.1.7. Arid Region of Central Australia

For the arid region of Central Australia, approximately corresponding to zone 5 of the ARR storm temporal patterns in ARR 1987 (Pilgrim, 1987), and covering the interior of South Australia, Western Australia and the Northern Territory, the data of Flavell et al. (1983), Kemp (1993), Board et al. (1989) may be used to guide selection of K_c values.

Predicted K_c values for the arid regions of South Australia (Equation (7.6.20)), Western Australia (Equation (7.6.25)) and Victoria (Equation (7.6.16)) are lower than K_c values for the higher rainfall areas of these states. Similar trends for lower K_c values in lower rainfall regions have been found by Yu (1990) and Kemp (1993). Equation (7.6.19) appears to be an anomaly since it predicts higher K_c values for the arid zone of the Northern Territory compared to the humid and transition zones.

Equation (7.6.25) for the wheatbelt, north-west and Kimberley region of Western Australia lies within the range of K_c values predicted by Equation (7.6.20) for the arid zone of south Australia. The data of Board et al. (1989) also agrees with equation Equation (7.6.25).

Therefore equation Equation (7.6.25) is recommended for the arid interior of Western Australia and the Northern territory, and equation Equation (7.6.20) for the arid region of South Australia.

6.2.1.8. Tasmania

Morris (1982) developed the following relation for 17 catchments (63 to 1780 km^2) using m = 0.75:

$$K_c = 4.86A^{0.32} \qquad (7.6.28)$$

Australian Rainfall and Runoff (Pilgrim, 1987) presents a relation developed by the Tasmanian Hydro Electric Commission for western Tasmania, with m = 0.75:

$$K_c = 0.86A^{0.57} \qquad (7.6.29)$$

Equation (7.6.28) and Equation (7.6.29) are in good agreement for catchments near to 1000 km^2 but Equation (7.6.28) predicts larger K_c values for smaller catchments.

In the absence of further data, equation Equation (7.6.29) is recommended for Tasmania.

6.2.2. Regional relationships for RORB using Area-Standardised Lag Parameter

Equation (7.6.2) to Equation (7.6.29) all show that the lag parameter K_c of RORB is strongly correlated with catchment area A raised to a power slightly greater than 0.5. Since stream lengths are also strongly related to catchment area raised to a very similar power, it follows that K_c will be related to stream length or a measure of stream length. One measure of stream length which has been adopted in RORB is the average flow distance d_{av}. McMahon and Muller (McMahon and Muller, 1983; McMahon and Muller, 1986) and Yu (1990) have used these relations to form an area-standardised lag parameter K_c/d_{av}. Kemp (1993) formed a similar area-standardised lag parameter $K_c/A^{0.57}$. Because of the strong relation between K_c and measures of area and stream length, the area-standardised lag parameter should be essentially independent of the catchment size. The area-standardised lag parameter can then be seen as analogous to lag parameters C , B and β in the WBNM, RAFTS and URBS models respectively.

Yu (1990) found that K_c/d_{av} increased as mean annual rainfall increased in Victoria (30 catchments) and western Australia (51 catchments), but not in New South Wales, Queensland or the Timor sea region of the Northern Territory (41 catchments in total). For all 122 catchments, the average value of K_c/d_{av} was found to be 1.09. Kemp (1993) found a similar increase of $K_c/A^{0.57}$ as mean annual rainfall increased for South Australia, Victoria, Western Australia and the Alice Springs region of the Northern territory. The effect appears to be more pronounced in the drier winter rainfall regimes.

Pearse et al. (2002) combined the data of Hansen et al. (1986), Dyer et al. (1995) and Yu (1990), for more than 220 catchments in Queensland, New South Wales, Victoria, Tasmania and Western Australia. The non-linearity parameter was set at m = 0.8. The mean value of K_c/d_{av} was found to range between 0.96 and 1.25, depending on the particular region. The results of Yu (1990) and Pearse et al. (2002) allow K_c to be estimated for any catchment by first calculating the average flow distance dav, then multiplying it by the appropriate area-standardised lag parameter value.

These results also indicate that many of the regional relations across Australia Equation (7.6.2) to Equation (7.6.29)) could be fitted by either a single relation or a small number of similar relations. For example, the data of Hansen et al. (1986) for 30 catchments (20 to 3910 km^2) produces the following relation between dav (km) and A (km^2):

$$d_{av} = 0.98A^{0.54} \tag{7.6.30}$$

Combining equation Equation (7.6.30) with the range of K_c/d_{av} values from 0.96 to 1.25 produces a general relation:

$$K_c = \mathrm{Coeff}.A^{0.54} \tag{7.6.31}$$

where the coefficient ranges from 0.94 to 1.22.

Equation (7.6.31) can be plotted for the mid-range coefficient value 1.08, together with the recommended relationships for the various regions of Australia, and is seen to lie in the middle of these relationships.

While the area-standardised lag parameter can be expected to be essentially independent of catchment size, it may be related to other variables. Dyer et al. (1995) developed regression relationships between K_c/d_{av} and a range of catchment, climatic and RORB model properties for seven groups. The method is also presented in Grayson et al (1996). Catchments were placed into groups based on hydrological similarity, utilising Andrews curves, rather than on geographical region. All values of K_c/d_{av} are for m = 0.8 and using a proportional loss rather than a continuing loss rate model. Data from 72 catchments from the east coast of Australia, Tasmania, the Adelaide Hills, and the south-west of Western Australia were used. The various regression equations, and the variables in them, were not consistent across the seven groups. Slope appeared in the equation for only one group. While reasonably strong regressions could be developed for the catchments in the data set, difficulties in assigning ungauged catchments to a particular group have been found to cause problems in application of the method (Perera, 2000; Pearse et al., 2002).

6.2.3. Regional Relationships for WBNM

In WBNM the non-linearity parameter is recommended to be set at *m* = 0.77, unless there is strong evidence to use another value. This is very close to the widely adopted value of *m* = 0.80 in RORB. With parameter *m* set, only the lag parameter C needs to be evaluated. As noted previously, parameter C is effectively an area-standardised value analogous to K_c/d_{av} in RORB. Therefore parameter C should be independent of catchment size. Additionally, if the value of the non-linearity parameter *m* is correct, parameter C should be independent of the flood size.

Parameter values have been derived for WBNM by Boyd et al. (1979), Boyd et al. (2002), Sobinoff et al. (1983), Bodhinayake (2004) and Boyd and Bodhinayake (2005). Plots of parameter C against catchment area A have shown no trend for C to vary with catchment size, indicate that the power of area A is satisfactory. The lack of dependence between the area-standardised form of the lag parameter in RORB and catchment area has also been noted by Pearse et al. (2002). Additionally, plots of C against the peak discharge of the recorded flood have shown no trend for C to vary with flood size, indicating that the non-linearity parameter *m* = 0.77 is satisfactory.

Bodhinayake (2004) investigated possible trends in parameter C against a range of storm and catchment characteristics. Storm variables which were considered included the peak discharge, rainfall depth, rainfall excess depth, rainfall intensity, location of peak burst within storm, and spatial distribution of rainfall. Catchment variables included area A, stream slope S_e, stream length L, length to centroid L_c, spatial distribution of area L_c/L, catchment shape A/L2, catchment elevation, number of rain days, and mean annual rainfall. The study used 251 storms on 17 catchments in eastern Queensland. While slight trends were apparent in some cases and for some subsets of catchments, there were no strong trends for C to vary with any of these variables. The independence of parameter C from these storm and catchment characteristics indicates that one value applies generally over a wide range of regions. A similar result has been obtained for the area-standardised lag parameter in RORB by Pearse et al. (2002).

Values of the lag parameter C calibrated for south and eastern Australia are:

For 207 storms on 17 coastal catchments in Queensland (164 to 7300 km^2), ranging from the North Johnstone to the Mary River, Bodhinayake (2004) obtained a mean value of parameter C of 1.47.

For ten catchments in the coastal region of NSW (0.4 to 250 km^2), Boyd et al. (1979) obtained a mean lag parameter C of 1.68. For 17 catchments (0.1 to 800 km^2) in the Newcastle, Sydney-Wollongong region Sobinoff et al. (1983) obtained a mean C of 1.16. Recent calibration of WBNM for 205 storms on 19 coastal catchments of NSW (0.2 to 6910 km^2) by Boyd and Bodhinayake (2005) obtained a mean C of 1.74.

For 59 storms on six catchments in Victoria on the coastal side of the Great Dividing Range, ranging from Bairnsdale to Ballarat (0.1 to 153 km^2) plus 45 storms on four catchments inland of the Great Dividing Range near Healseville and Stawell (63 to 259 km^2), Boyd and Bodhinayake (2005) obtained a mean value of C = 1.74.

For 90 storms on eight catchments in the Adelaide Hills near to Adelaide (4 to 176 km^2), Boyd and Bodhinayake (2005) obtained a mean value of C = 1.64.

The small range of these mean parameter values corresponds to the similar small range of the area-standardised parameter K_c/d_{av} in RORB found by Pearse et al. (2002). Boyd and

Bodhinayake (2005) calculated a mean value of parameter C for all 54 catchments in Queensland, New South Wales, Victoria and South Australia of 1.64, and 1.59 when the parameter values were weighted by the number of storms on each catchment.

> With no strong regional trends being apparent, and no strong relationships between parameter C and catchment or storm characteristics, an overall mean value of parameter C = 1.60 is recommended for these states of Australia.

6.2.4. Relationships between RORB, WBNM, RAFTS and URBS Lag Parameters

As noted previously, all four runoff-routing models contain area-standardised lag parameters. These are K_c/d_{av}, C, B and β of the RORB, WBNM, RAFTS and URBS models respectively. It could therefore be expected that these parameters will be related to one another. For example, comparing equations for WBNM with equations for RORB reveal that $CA_i^{0.57}$ in WBNM corresponds to $(K_c / d_{av}).L_i$ in RORB. Note that the area term A_i and stream length term L_i in these equations refer to subcatchments and stream segments rather than to complete catchments.

Measures of stream length, such as L and d_{av} (Equation (7.6.30)) are strongly related with catchment area, and it is reasonable to assume that stream segment lengths are also strongly correlated with subcatchment areas. Replacing the L_i term by $A^{0.55}$, it is seen that parameter C of WBNM should be directly proportional to K_c/d_{av} of RORB. From the previous sections the average value of C is close to 1.60 and the average value of K_c/d_{av} is 1.1 (range 0.96 to 1.25). Therefore a relationship between these two parameters is:

$$C = 1.45\, K_c/d_{av} \quad (7.6.32)$$

Similar analysis indicates that parameter β of URBS should be directly proportional to K_c/d_{av}. For RAFTS the proportionality coefficient should be related to K_c/d_{av} but with an adjustment required for the slope term S.

It should be noted that the correspondence between the area-standardised lag parameters of the various models depends slightly on the power to which area A is raised, as well as the non-linearity parameter *m*, however these are not too dissimilar in the four models. The particular ratio between the parameters will depend on the way in which the lag parameter is incorporated into flood routing in the particular modelling platforms, as well as the method adopted for stream channel routing. The ratio 1.45 between RORB and WBNM will not apply to RAFTS and URBS.

6.3. Modelling Urban Catchments

Increased flood discharges in urban or partially urbanised catchments can be attributed to two factors. The increased proportion of paved or impervious surfaces produce greater runoff volumes, and the decreased lag times for the runoff produces higher peak discharges. These increases are not the same for all floods, being more pronounced for the smaller more common events. Data given by Cordery (1976a), Codner et al. (1988) and Mein and Goyen (1988) indicate that for 10% Annual Exceedance Probability events, urban flood peak discharges increase by 2 to 5 times, while for 1% Annual Exceedance Probability events urban peaks increase by less than two times.

Increased runoff volumes from paved surfaces result from decreased rainfall losses.

The decrease in lag time can be attributed to replacement of vegetated overland flow surfaces and natural stream channels by more hydraulically efficient paved surfaces, gutters, pipes and channels. Ratios of lag times in urban compared to otherwise equivalent natural catchments typically range from 0.1 to 0.5 (Cordery, 1976b; Codner et al., 1988; Mein and Goyen, 1988; Boyd et al., 1999; Boyd et al., 2002). Decreases in lag time have been related to the fraction of the catchment which is urbanised by Aitken (1975) and NERC (1975). Other studies by Rao et al. (1972), Crouch and Mein (1978), Desbordes et al. (1978), Schaake et al. (1967) and Espey et al. (1977) relate lag time to the impervious fraction. A survey of these relations is given by Boyd et al. (1999) and Boyd et al. (2002).

All of these studies show a decrease in lag time as the catchment becomes more urbanised. Typically, the lag reduction is expressed in terms of the urban fraction U in the form (1+U)z where *z* ranges between –1.7 and –2.7, with an average near to –2.0. Equation 5.3.4.19 adopts *z* = -1.97 for RAFTS, while equation 5.3.4.20 adopts *z* = -2.0 for URBS. A value of *z* = -2.0 in this relation produces a lag ratio of 0.25 for a fully urbanised catchment.

The urban fraction urban often does not fully describe the state of urbanisation, since a 100% urban catchment can be residential with typically 30% impervious surfaces, or it can be a high density commercial centre with close to 100% impervious. Typical relationships between the impervious and the urban fraction are given by Boyd et al. (1993) and Boyd et al. (2002). The RAFTS model accounts for this by allocating an equivalent urban fraction U to each level of impervious fraction. For a fully impervious surface, this produces a lag ratio of 0.11.

When a subcatchment is partly urbanised, it can be modelled in a lumped form whereby a single hydrograph is calculated for the combined pervious and impervious surfaces, using a reduced lag time. This is often done in the RORB, RAFTS and URBS models. Alternatively, the subcatchment can be split into separate pervious and impervious surfaces with separate lag times and separate hydrographs calculated for each surface. This is the recommended method for WBNM, where the lag ratio for fully impervious surfaces is set at 0.10, similar to the value recommended in RAFTS. However, all models can be configured to operate in either lumped or split form, and RAFTS has been found to produce good results in the split form for catchments in the ACT (Knee and Bresnam, 1993). Split pervious and impervious modelling is similar to the procedures used in detailed urban drainage modelling platform such as DRAINS.

Urban catchments have other features which need to be considered when setting up a model. During large storms flows may be diverted out of the catchment's stream network to form new overland flow routes. This can happen particularly when culvert or bridge openings become blocked by debris. The model should be set up to reflect these alternative flow paths. Another feature requiring consideration is that runoff from small development sites, and particularly when onsite detention storage is used to reduce flood peaks, will require routing calculations at small time steps and with small discharges. The stream network runoff-routing models currently used in Australia all have these capabilities.

6.4. References

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Chapter 7. Validation and Sensitivity Testing

William Weeks, Erwin Weinmann

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7.1. Validation

After the catchment modelling system calibration has been finalised, the final step in acceptance of the model is the validation process. The calibration has resulted in model parameters that are suitable for application to the design problem, but validation provides a means of ensuring that the parameters are suitable and that the catchment modelling system can be applied to the design problem required. The validation process is therefore a confirmation that the calibrated catchment modelling system is fit for the required purpose.

Validation can be associated with independent verification of the model parameters. In this process, the calibrated catchment modelling system is tested with an independent data set that was not used in the parameter estimation process. While this does provide additional confirmation that the catchment modelling system is performing adequately, calibrations are usually very limited in the availability of data, and there are usually insufficient events to allow this independent assessment.

Validation therefore is a careful review of the catchment modelling system and its application to the problem at hand, so must consider the suitability of both the catchment modelling system and the parameters.

The first step is to review whether the catchment modelling system applied is appropriate for the application required. The questions are as follows.

- Is the model suitable for the problem being investigated?
- Does the model include sufficient detail in the spatial coverage of flooding?
- Does the model represent the flooding questions with sufficient accuracy to answer the required questions?
- Can the model be extrapolated accurately to rarer (or sometimes smaller) floods from the flood magnitudes used to establish it?
- Can the model be used to represent the range of design conditions (such as developed conditions or flood mitigation options) that are required in the design applications?

In addition to the review of the model and calibration, additional validation can be considered by reconciling the model performance with an alternate independent estimate. For example, for hydrology calculations, rainfall based methods can be reconciled with streamflow based methods or two alternative models may be calibrated separately and the results compared.

A special form of validation is for hydrologic models that are used to estimate probability based design flood characteristics. In these cases the main performance criterion for the model and the adopted parameter set is that the model is able to transform the probability based design inputs (design rainfalls, design losses and baseflows) into probability based flood outputs (flood hydrographs and flood levels) without introducing any probability bias ie. Probability neutral. Here the validation has to be against independent design flood estimates, e.g. from the flood frequency estimation procedures covered in Book 5.

In summary, the validation process is a critical independent review of the model establishment and performance to ensure that it is appropriate for the intended application.

If the model is determined to be appropriate, it can be applied to the required design problem. If the model with the adopted parameter set does not perform satisfactorily, the model establishment should be checked first to ensure that it adequately represents the important characteristics influencing flood behaviour. Only if this is found to be satisfactory should further effort be put into reviewing and adjusting model parameters.

7.2. Sensitivity Testing

Sensitivity testing of model platform parameters, uncertainties in input data and the model's schematisation (resolution) should be a regular part of a practitioners activities, especially for inexperienced practitioners, whilst calibrating a model. It also plays a useful role for establishing the uncertainty of uncalibrated models.

For models that are well-calibrated to a range of flood events and later verified, considerable confidence can be had in the model's ability to reproduce accurate flood levels. This in turn means that factors of safety such as the design freeboard applied to flood planning levels can be kept to a minimum.

However, for uncalibrated or poorly calibrated models less confidence can be had in the model's accuracy, and greater factors of safety (e.g. larger freeboards) should be applied to reflect the greater uncertainty (further discussion on uncertainty can be found in Book 7, Chapter 9). To quantify these uncertainties, sensitivity testing could be carried out where a model's calibration is non-existent or poor.

Examples of sensitivity testing to help quantify a model's uncertainty are:

- Adjust hydraulic roughness parameters values up and down by 20%;
- Adjust lag parameters;
- Increase inflows by 20%;
- For downstream boundaries, not at a receiving water body such as the ocean, vary the stage discharge or water level upwards to check that the water levels in the area of interest are not greatly affected;
- Apply blockages and greater losses to hydraulic structures and inlets; and
- Apply lower discharge coefficients across embankments such as roads.

Other useful sensitivity tests include:

- Making the model's resolution finer to check that results do not demonstrably change; and
- Varying the timestep and other computational parameters.

Sensitivity testing is also a very important part of developing a modeller’s knowledge base and should be encouraged wherever possible.

> After a few weeks of pulling their hair out trying to calibrate to a well-defined flood mark in a house (the model was calibrating well elsewhere), the modellers called the owner of the house. After chatting for a while the owner suddenly remembered “my Dad had the house raised after that flood”. Once the flood mark was adjusted by how much the house was raised, a good calibration was revealed! The modellers regretted not making that call a few weeks earlier…

Chapter 8. Application to Design

William Weeks, Erwin Weinmann

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8.1. Overview

Once the practitioner is satisfied with the calibration and validation, the next step in the application of a catchment modelling system is to apply it to the design problem. Australian Rainfall and Runoff is principally concerned with design flood estimation problems where floods of defined probabilities are required, but other applications are required for flood forecasting and warning or for assessment of impacts. A concern is that the calibration and validation processes concentrate on recorded historic flood events, whereas the design applications are more theoretical probabilistic events.

In the analysis of these probabilistic events, an important objective is to transfer probabilistic rainfalls into probabilistic flood levels, through the calculation of flood discharges. These design events are quite different from the historic floods and care must be taken in transferring the catchment modelling system application from the variable historic events into the design results.

As discussed in Book 7, Chapter 7, the parameters selected for application to the design conditions must be appropriate for the required application as well as consistent with the calibration to the available historic data.

There are therefore three conditions where model parameters may be required:

- *Historic Floods* - These are the floods where the data has been used to estimate parameters and to validate the models. Where there is more than one flood event, there may be a variety of conditions represented, with different spatial and temporal rainfall distributions possible. The flood events will sample a limited range of conditions that have applied during the period when data could be collected and these may not necessarily be representative of the conditions where the model must be applied. In addition, catchment conditions may have changed since the historic flood event occurred. Historic floods may also be analysed in the "design" application of models where flood impacts may be required to assess how development would have affected a historic flood for example.

- *Design Applications* - This is the main application where models discussed in Australian Rainfall and Runoff will be required and require results for floods of defined probability to be calculated. This is a more theoretical application than the analysis of historic floods and the parameters need to be established to ensure that the probability is calculated correctly. It is likely that the probabilistic floods calculated will be larger than the historic floods used to estimate the model parameters. The probabilistic design flood estimates must consider the relevant requirements. In some cases, flood peaks may be the only requirement, while flood hydrographs or flood volumes may be relevant at other times. There are different issues for each requirement.

- *Real Time Flood Estimation* - This is the requirement to use the model for a flood forecasting and warning application. This is different from the design application since timing is critical and the parameters must be available to carry out the analysis as the event is occurring. This is a far more complex application than the design situation, and while similar conditions apply in model application, this chapter concentrates on the design conditions.

This chapter concentrates on the probabilistic applications, though there are some similarities with the others.

8.2. Issues with Historical Calibration Floods

8.2.1. Introduction

Where parameters estimated from historical events must be transferred to design applications, a common concern is how representative the historic events are of the design flood events that must be estimated with the catchment modelling system.

8.2.2. Magnitude of the Calibration Events

A common issue is that the historic calibration events are relatively frequent, while the design applications may be needed for floods up to 1% Annual Exceedance Probability or rarer. It is therefore important that the model parameters selected for design application should still be appropriate for analysis of the rarer flood events.

A common assumption is that the model parameters calibrated on relatively frequent events remain constant for all rarer events. This may or may not be correct, so this assumption should be checked with regard to the representativeness of the calibration floods and with the model processes and whether there is a change in response for rarer flood events.

> In general constant parameters are recommended for the range of design events unless there is some evidence otherwise.

8.2.3. Calibration Event Conditions

The calibration events used to determine catchment modelling system parameters are generally all that is available, and the practitioner must apply the data from these events without the luxury of making a selection of the most appropriate events.

During calibration the practitioner must carefully review the properties of the historic floods used for calibration and determine how appropriate these are to be applied to the design problem. For example, the available calibration floods may be localised on a part of the catchment while the design flood event should be a more widely distributed event. On larger catchments, floods may be usually produced from a part of the catchment and the actual contributing section may vary from one event to another. The design case must therefore allow for the different catchment properties while estimating the probabilistic floods correctly. Some of these issues are discussed in Book 4 but there may be an impact on the transfer of the model parameters from the historic calibration events to the design flood events.

The calibrated parameters are for the situation/time when the calibration event occurred. However, there may be significant changes from one event to another. For example, in agricultural regions, the pattern of cropping may be different from one event to another. These varying catchment conditions may be considered in the individual calibration events, but they then need to be generalised for the design application. There are questions concerning how this is implemented. For example, sugar cane agriculture has areas of very high floodplain roughness in some locations and areas of fallow ground in other parts. These patterns vary from year to year and are difficult to determine for historic events. There is a question of the “average” conditions that should apply for the design application. A common approach is to adopt an average value of two very different conditions and then carry out some sensitivity tests to assess the impact of changes in the pattern of agriculture.

Similarly in arid areas, the antecedent conditions may have a major impact on catchment conditions for individual flood events, but these conditions then need to be represented in the design situation.

8.2.4. Applied Parameters

Calibration usually works with historic flood events while the design requirements are for probabilistic events. The parameters calculated for the historic recorded flood events may not be applicable to the design flood events and the results may not be consistent.

It is therefore important to confirm the model performance with probabilistic results. For situations where sufficient streamflow gauging is available, the model parameters can be confirmed using the Flood Frequency Analysis results to confirm that the model is representing the probabilistic flood discharges. Where there is insufficient streamflow records for a Flood Frequency Analysis, the model can be cross checked with a regional flood frequency results (Book 3, Chapter 3). Similarly, the model output can be confirmed with other anecdotal data, to confirm that the parameters are appropriate for the design application.

When applying hydrologic and hydraulic models to design situations, there are additional details that add complexity to the process. Often the historic floods are calibrated to the conditions that apply when the flood event occurred, so there are set values for antecedent conditions, losses, baseflow and the particular conditions that applied in the event, such as spatial or temporal patterns of rainfall. These additional factors are often not a part of the calibration process but must be incorporated into the design conditions.

8.3. The ARR Data Hub

The ARR Data Hub holds the design input data required for the application of ARR for design flood estimation. By inputting catchment centroid or a shape file you can download: the River basin, long duration ARF, Short duration ARF, storm loss value, pre-burst and temporal patterns. Entering the catchment outlet location allows the practitioner to download baseflow factors. As the data underlying ARR will progressively change as new data and techniques are available practitioners are recommended to visit the data hub at the start of each project. It is accessible at http://data.arr-software.org/. The data can be downloaded as a text file and included as an appendix to a project report.

Chapter 9. Uncertainty Determination

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9.1. Introduction

An overview of the various sources of uncertainty relevant to flood estimation and their treatment is provided in Book 1, Chapter 2. This guidance distinguishes between two broad types of uncertainty, namely:

- Aleatory (or inherent) uncertainty, which refers to uncertainty attributed to natural randomness or natural variability observed in nature; and,
- Epistemic (or knowledge-based) uncertainty, which refers to uncertainty attributed to incomplete/imperfect knowledge of a physical system (and hence its model), and to the inability to measure it precisely if at all.

Practical procedures for dealing with *aleatory uncertainty* are provided in Book 4, Chapter 4, whereas the focus of this chapter is on the assessment of *epistemic uncertainty*. Procedures for dealing with epistemic uncertainty for some specific methods are described elsewhere in ARR, and in particular it is worth noting the rigorous procedures provided for estimates of peak discharges using flood frequency and regional flood prediction methods, as described in Book 3.

It is perhaps a common view amongst practitioners that uncertainty analysis is too difficult to undertake. It is certainly true that assessing uncertainty takes additional time and effort, but there are uncertainty assessment frameworks with generic applicability to a range of practical problems (e.g. Pappenberger and Beven (2006); Pappenberger et al. (2006); Doherty (2016); Kuczera et al. (2006); Palisade Corporation (2015); Vrugt and Braak (2011)). For those with the necessary skills and interests, it is reasonable to assume that the effort required to become proficient with such tools will return benefits across a range of projects. That said, it would appear that specialists who are comfortable with uncertainty analysis tend to underestimate the depth of tacit knowledge required to implement and interpret such schemes, and the entry hurdle for many practitioners is a material one. Regardless, at this point in time it is acknowledged that the available hydrological and hydraulic models commonly used in Australia do not include the capability to assess uncertainty. It is expected that this situation will improve with time.

The intended audience for this Chapter are interested practitioners who do not have specialist training in the application of uncertainty techniques. The procedures described in this Chapter are not intended to cover the steps required to estimate the true uncertainty associated with input data, model parameters, and model structure. Rather, a small number of practical procedures are presented in the hope that these will allow practitioners to better understand (and communicate) the nature of uncertainty associated with selected key aspects of the flood estimates provided.

Book 7, Chapter 9, Section 2 discusses the role of sensitivity analysis in the assessment of uncertainty, and this is followed by a discussion (Book 7, Chapter 9, Section 3) of some simple analytical approaches relevant to error propagation. Book 7, Chapter 9, Section 4 discusses the application of Monte Carlo methods that can be used to assess uncertainty. Each method is supported by illustrative examples of their usage.

9.2. Sensitivity Analysis

Sensitivity analysis is a standard engineering technique that provides information on how model outputs are affected by changes in model inputs. Such analyses do not provide estimates of uncertainty, but they do provide a useful means of identifying which factors have greatest influence on the outcome. This insight, combined with some judgement regarding the relative accuracy of the different factors, can highlight which areas of analysis warrant further investigative effort. Importantly, such analysis can also reduce the dimensionality of subsequent uncertainty analysis so that effort is expended only on the factors of most importance.

There are a variety of ways that the sensitivity of an outcome to uncertainties can be represented, and two simple examples are shown in Figure 7.9.1. The tornado diagram provides a simple summary of the sensitivity of an outcome to reasonable estimates of upper and lower ranges, and the spider plot illustrates the dependence of the outcome on the percentage deviation of the key parameters from their adopted values.

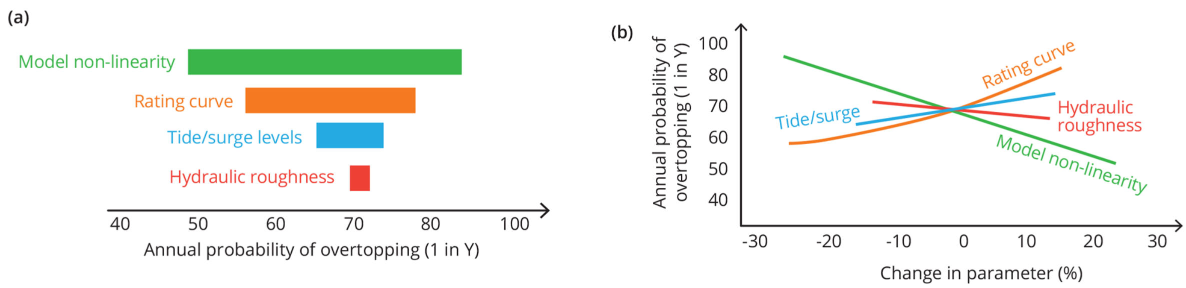

Figure 7.9.1. Representation of Relative Uncertainty of Outcome to Uncertainties Using a (a) Tornado Diagram and (b) Spider Plot

Changes in model input values can affect model outputs in different ways, and any dependency between inputs can mask the manner in which factors combine to influence the outputs. In addition, the nature of the factors which most influence the outcome may well vary with event magnitude. For example, the sensitivity to non-linearity in storage-routing models is dependent on the degree to which estimates are extrapolated beyond the magnitude of floods used for calibration; the reasonable range of estimates of roughness parameters in a hydraulic model may vary with the depths of flow considered. Accordingly, judgement needs to be used when selecting which factors to vary over a particular set of conditions, and care is needed to ensure that the range of values considered takes account of the possible dependencies.

Care also needs to be taken when considering the parameter ranges over which the sensitivity is assessed. The upper and lower limits of parameter values considered should reflect a similar range of notional uncertainty in each, otherwise misleading inferences may be drawn about the sensitivity of their impact on the outcome. More details on the uses and application of sensitivity analyses can be found in Loucks et al. (2005).

9.3. First Order Approximation Method

The purpose of introducing this simplified method of uncertainty analysis is to illustrate the general nature of how errors in model inputs and parameters can propagate through a model to produce errors in the model outputs. The first order error propagation method can be used in a similar fashion to sensitivity analysis to firstly identify the relative importance of different error sources and secondly to assess how the influence of different error sources changes with event magnitude and frequency.

9.3.1. General Approach

The equation for error propagation for a function *f* of independent variables *x, y, z* is (Haan, 2002):

$$s_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 s_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 s_y^2 + \left(\frac{\partial f}{\partial z}\right)^2 s_z^2 + \ldots} \tag{7.9.1}$$

where s_f and s_x, s_y, s_z are respectively the standard deviations of the function and the independent variables. This approximation assumes that the errors are normally distributed and independent.

This error propagation equation can be used to gain an approximate indication of how errors in the independent variables translate into errors in the estimation results. The following example illustrates this and compares the errors in the estimates from three different methods.

9.3.2. Example: Flood Volume of an n-Day Flood Event with AEP 1 in T

A number of approximate methods can be used to estimate the flood volume V_x for a design flood event of given AEP and duration. Here the errors in volume estimates for three different methods are derived and compared. The assumed percentage errors in the inputs to the different methods have been selected somewhat arbitrarily but should be indicative of the expected error magnitude.

A. *Estimate derived using a transposition model*

If an estimate of the flood volume at gauged site *Y* is available from a frequency analysis of flood volumes, the flood volume (*V*) at ungauged site *X* can be estimated from a scaling relationship:

$$V_x = V_y\left(\frac{A_x}{A_y}\right)^m = V_y(R)^m \tag{7.9.2}$$

where *A* denotes the area of each catchment, *m* is a scaling parameter, and the subscripts refer to the individual catchments. Assuming that the estimate of the ratio of the areas of the two catchments (*R*) is error free but that the volume estimate at site *Y* (V_y) and the exponent of the scaling relationship (*m*) have errors s_V and *sm*, respectively, then the relative error in V_x can be calculated as:

$$\frac{s_{Vx}}{V_x} = \sqrt{\left(\frac{s_{Vy}}{V_y}\right)^2 + \left(ln(R) \quad s_m\right)^2} \tag{7.9.3}$$

Estimates of errors in the transposed flood volumes based on Equation (7.9.3) are provided in Table 7.9.1 for a range of representative input errors and parameter values. The results indicate that errors in the flood estimate at the gauged site are directly transferred to the estimate at the ungauged site, so errors increase as AEP decreases. Scaling to different catchment areas introduces little extra error as long as the catchment areas differ by no more than about 20 to 30% and the exponent in the scaling equation can be estimated to within about 10% accuracy. Scaling up and scaling down introduces similar errors.

Table 7.9.1. Errors Flood Volumes Estimated Using a Transposition Model for a Range of Assumptions.

AEP	Variables		Output/ Input	Input Errors		Output Error
R	m	V_x/V_y	s_{V_y}/V_y	s_m/V_y	s_{V_x}/V_x	
0.5 to 0.1	0.8	0.7	0.86	0.10	0.10	0.101
	0.8	0.9	0.82	0.10	0.10	0.102
	0.8	0.7	0.86	0.10	0.20	0.105
	0.5	0.7	0.62	0.10	0.10	0.111
	0.5	0.7	0.62	0.10	0.20	0.139
	1.25	0.7	1.17	0.10	0.10	0.101
	1.25	0.7	1.17	0.10	0.20	0.105
	2.0	0.7	1.62	0.10	0.10	0.111
	2.0	0.7	1.62	0.10	0.20	0.139
0.01	0.8	0.7	0.86	0.20	0.10	0.201
	0.5	0.7	0.62	0.20	0.10	0.206
	0.5	0.7	0.62	0.20	0.20	0.222
0.001	0.8	0.7	0.86	0.40	0.10	0.400
	0.5	0.7	0.62	0.40	0.10	0.403
	0.5	0.7	0.62	0.40	0.20	0.412

B. *Estimate derived using a runoff coefficient model*

This method assumes that a certain percentage of the average design rainfall depth *P* over the catchment for the given duration and AEP 1 in T is converted to a corresponding flood volume at the catchment outlet. The flood volume can thus be computed as

$$V_x = CAP \tag{7.9.4}$$

where *C* is a volumetric runoff coefficient and *A* is the catchment area.

Assuming that all the three variables have estimation errors associated with them, the relative error in the estimated flood volume can be approximated as:

$$\frac{s_{Vx}}{v_x} = \sqrt{\left(\frac{s_C}{C}\right)^2 + \left(\frac{s_A}{A}\right)^2 + \left(\frac{s_P}{P}\right)^2} \tag{7.9.5}$$

where s_{V_x} and s_C, s_A, s_P are respectively the standard deviations of the estimated volume and the three independent variables used in the estimate. Estimates of errors in the flood volumes based on Equation (7.9.5) are provided in Table 7.9.2 for a range of representative input errors and parameter values. The results show that the relatively large error in the volumetric runoff coefficient *C* dominates the error in the estimated flood volume.

Table 7.9.2. Errors Flood Volumes Estimated Using a Runoff Coefficient Model for a Range of Assumptions

AEP	Input Errors			Output Error
s_C/C	s_A/A	s_P/P	s_{V_x}	
0.5 to 0.1	0.5	0.00	0.1	0.51
	0.5	0.05	0.1	0.51
	0.5	0.05	0.2	0.54
0.01	0.4	0.00	0.2	0.45
	0.4	0.05	0.2	0.45
0.001	0.3	0.00	0.3	0.42
	0.3	0.05	0.3	0.43

C. *Estimate derived using a water balance model*

The flood volume can also be estimated from a water balance equation for the catchment over the duration of interest, in this case expressed in terms of design values for the different terms in the equation, (average depths over the catchment area *A*, in mm):

$$\frac{v_x}{A} = I - L + BF \tag{7.9.6}$$

where *I* is the design event rainfall, *L* is the total loss and *BF* the total baseflow contribution over the duration of the flood event. The loss and baseflow values are assumed to be invariant with AEP.

The relative error in the estimated flood volume can then be calculated as:

$$\frac{s_{v_x}}{v_x} = \frac{1}{v_x}\sqrt{s_I^2 + s_L^2 + s_{BF}^2} \tag{7.9.7}$$

Estimates of errors in the transposed flood volumes based on Equation (7.9.7) are provided in Table 7.9.3 for a range of representative input errors and parameter values. The results show that for frequent flood events the errors in the loss and baseflow values play an important role in the flood volume estimates, which can have large errors, while for very rare events the errors in estimated flood volumes are dominated by errors in the design rainfalls.

Table 7.9.3. Errors Flood Volumes Estimated Using a Water Balance Model for a Range of Assumptions

AEP	Input Variables			Output
I	L	BF	V_x	
0.5	65	40	20	45
0.1	100	40	20	80
0.01	150	40	20	130

AEP	Input Variables			Output
0.0001	500	40	20	480

Table 7.9.4.

AEP	Input Errors (Relative)			Input Errors (Absolute)				
s_l/I	s_l/L	s_{BF}/BF	s_l	s_l	s_{BF}	s_{V_x}	s_{V_x}/V_x	
0.5	0.2	0.3	0.4	13.0	12.0	8.0	19	0.43
0.5	0.1	0.2	0.3	6.5	8.0	6.0	12	0.27
0.1	0.2	0.3	0.4	20.0	12.0	8.0	25	0.31
0.1	0.1	0.2	0.3	10.0	8.0	6.0	14	0.18
0.01	0.2	0.3	0.4	30.0	12.0	8.0	33	0.26
0.01	0.1	0.2	0.3	15.0	8.0	6.0	18	0.14
0.0001	0.3	0.3	0.4	150.0	12.0	8.0	151	0.31
0.0001	0.2	0.2	0.3	100.0	8.0	6.0	100	0.21

Evaluation of the three models

The comparison of the error estimates from the three methods indicates that for relatively frequent events the transposition model (A) using an estimate based on flood frequency analysis performs best. Method (B) is dominated by relatively large errors in the runoff coefficient for all flood event magnitudes and frequencies. Method (C) performs best for rare to very rare events, where errors in the loss and baseflow play only a minor role.

9.4. Monte Carlo Simulation

9.4.1. General Approach

Monte Carlo simulation provides an alternative practical means for assessing how uncertainties in input parameters propagate through to the results of interest. Book 4, Chapter 4 describes the formulation and implementation of Monte Carlo procedures for the analysis of joint probabilities, and these same procedures may be applied to the assessment of uncertainty; however, rather than sampling from distributions representing natural variability, the stochastic samples are generated from distributions that characterise uncertainty in the inputs.

A general framework for how Monte Carlo simulation may be used to assess uncertainty is illustrated in Figure 7.9.2. The area of light-blue shading in this figure represents the main elements used to consider the joint interaction of the factors that are subject to natural variability (aleatory uncertainty), as discussed in detail in Book 4, Chapter 4 (Figure 4.4.7). The outer loop (in green) represents the additional simulations undertaken in which the parameters are stochastically sampled from distributions representing uncertainty in the inputs. That is, undertaking the inner loop of simulations yields an estimate of exceedance probability that a particular outcome might be exceeded (step D in Figure 7.9.2), and the outer loop provides an estimate of uncertainty of the derived quantile (step E). Of course, this framework could be simplified to provide an assessment of the uncertainty in the magnitude only of the outputs, in which case only the deterministic modelling within the blue shaded area is required (step C). The additional simulations required to consider epistemic uncertainty increases the number of simulations by up to two orders of magnitude. For example, if a stratified sampling scheme used 5000 simulations to derive a frequency curve of outputs, then around 500 000 simulations would be required to derive the corresponding 90% confidence limits.

Details of the simulation procedures required to undertake Monte Carlo simulation are provided in Book 4, Chapter 4. Two examples are provided below which illustrate application of these procedures. One example is used to assess the errors in the transposition of flood volumes (model A, as outlined in the preceding section), and the other extends the worked example presented in Book 4, Chapter 4, Section 4 for the analysis of concurrent tributary flows. The first example just considers the uncertainty in the magnitude of the outcome, the second considers the uncertainty in both its magnitude and frequency.

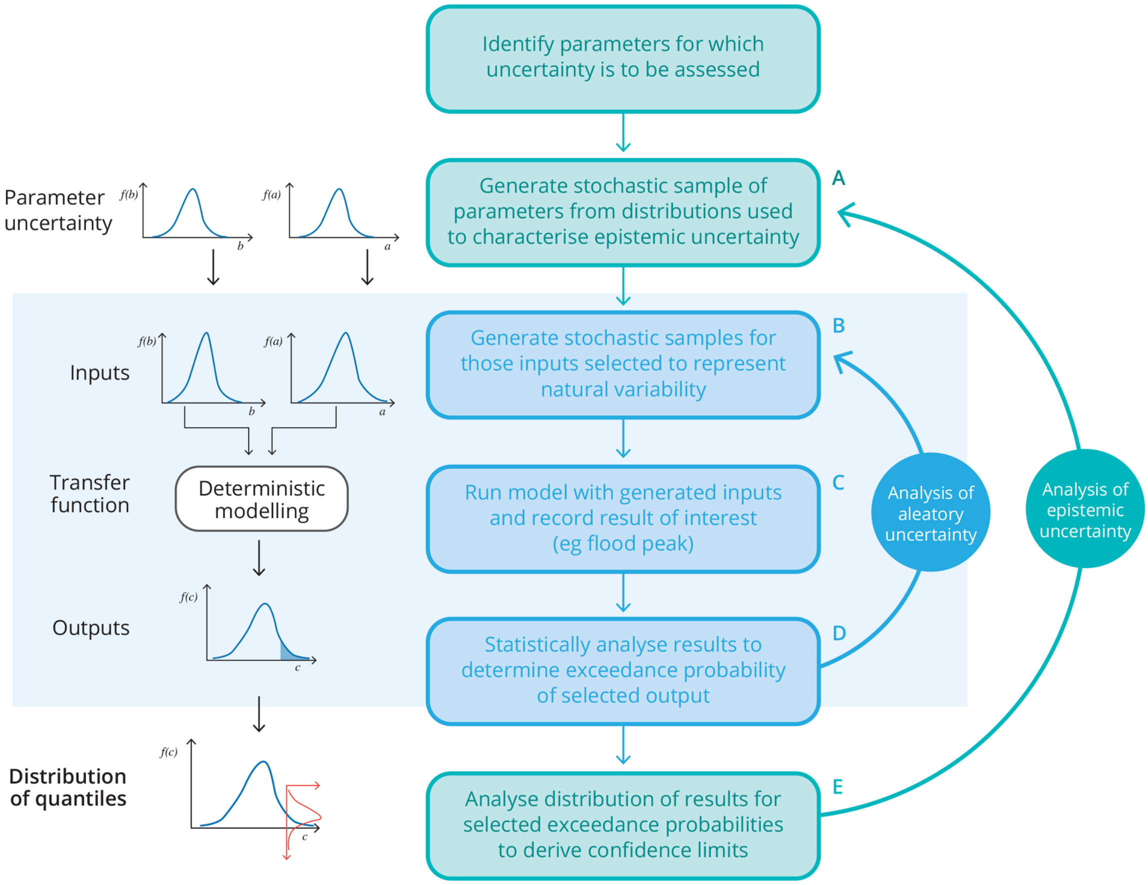

Figure 7.9.2. General Framework for the Analysis of Uncertainty using Monte Carlo Simulation.

9.4.2. Example: Flood Volume of an n-Day Flood Event with AEP 1 in T

A simple Monte Carlo scheme may be implemented in standard spreadsheet software to assess the propagation of uncertainty in the transposition example (Equation (7.9.2)), as shown in Figure 7.9.3. The approach is simply to generate a large number of normally distributed values about the mean estimates of m and $V_{y,}$, where the standard deviation of the sample reflects the magnitude of the errors. This is achieved by generating a sample of normally distributed values with a mean of zero and a standard deviation equal to s_m and s_v.

The steps required to do this are described in Book 4, Chapter 4, Section 3. For this example 2000 random numbers uniformly varying between 0 and 1 are generated for each of the variables V_y and m, as shown in columns 2 and 5 of Figure 7.9.3. The relative errors associated with V_y and m are assumed to be 10% and 20%, the ratio of catchment areas (R) is assumed to be 1.25 and the value of the exponent (m) is 0.7. The standard normal variates corresponding to the uniform random numbers are computed (columns 3 and 6), and these are multiplied by the selected variable values and their respective error terms (s_m, s_v) to yield 2000 stochastic values of V_y and m (columns 4 and 7). These steps yield a sample of values with a mean of zero and a standard deviation equal to their respective errors (s_m, s_v). Values of V_x are computed using Equation (7.9.2) for each pair of stochastically generated values of m and V_y (column 8). The standard deviation of these values represents the error about the mean estimate of V_x, and for the sample shown in Figure 7.9.3 this is found to be 3.11; when expressed as a proportion of the mean (0.108), this is similar to the result found by First Order Approximation, as shown in the 6th row of entries in Table 7.9.1.

The sample size is selected by trial and error such that successive estimates of the uncertainty change little with repeated stochastic samples. A sample size of 100 yields estimates of uncertainty that vary by around 10% of the mean value, and that obtained using a sample of 2000 vary by around only 1%.

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
No.	Uncertainty in V_y			Uncertainty in m			V_x
	N(0,1)	Zstd	V_y	N(0,1)	Zstd	m	
1	0.87	1.12	27.79	0.58	0.21	0.73	32.71
2	0.68	0.47	26.18	0.65	0.39	0.75	30.98
3	0.52	0.06	25.14	0.52	0.04	0.71	29.43
4	0.06	-1.51	21.21	0.70	0.52	0.77	25.21
5	0.84	1.00	27.51	0.57	0.17	0.72	32.33
6	0.12	-1.16	22.09	0.56	0.15	0.72	25.94
7	0.16	-1.01	22.47	0.00	-4.02	0.14	23.17
8	0.22	-0.78	23.05	0.96	1.73	0.94	28.44
9	0.32	-0.48	23.80	0.85	1.04	0.85	28.75
10	0.39	-0.27	24.32	0.06	-1.59	0.48	27.05
	⋮						⋮
1994	0.69	0.48	26.20	0.53	0.08	0.71	30.71
1995	0.39	-0.28	24.30	0.70	0.52	0.77	28.87
1996	0.20	-0.85	22.87	0.25	-0.69	0.60	26.17
1997	0.86	1.10	27.74	0.47	-0.08	0.69	32.35
1998	0.76	0.69	26.73	0.26	-0.64	0.61	30.64
1999	0.56	0.15	25.39	0.05	-1.66	0.47	28.18
2000	0.80	0.83	27.07	0.30	-0.53	0.63	31.12

R	1.25
m	0.7
s_m	0.2
s_v	0.1
Av(V_x)	28.79
s.d.(V_x)	3.11

Figure 7.9.3. Monte Carlo simulation of transposed flood volumes

9.4.3. Example: Flood level downstream of the confluence between two rivers

This example is based on the case study presented in Book 4, Chapter 4, Section 4. The example involves deriving a level frequency curve for a point below the confluence of two streams, where hydraulic modelling is used to estimate flood levels as a function of the coincident flood maxima.

The analysis presented in Book 4 demonstrates the use of the Total Probability Theorem in combination with a stratified sampling scheme to derive quantiles of flood levels below the confluence. The analysis presented here extends that original analysis, and shows how Monte Carlo simulation can be implemented in spreadsheet software to derive confidence limits for the derived flood levels. In essence, this example follows the framework illustrated in Figure 7.9.2, where the steps analysing aleatory uncertainty (blue shading) are described in Book 4, Chapter 4, Section 4, and those associated with the analysis of epistemic uncertainty are presented below.

The analysis is subject to three sources of uncertainty, namely the errors associated with:

- the parameters of the log-Normal distribution fitted to the flood maxima;
- the estimate of correlation between flood maxima in the two streams; and
- the estimates of the corresponding downstream flood levels from the hydraulic modelling.

The separate treatment of these uncertainties is discussed below.

Uncertainty in parameters of the flood frequency model

The assessment of uncertainty in the log-Normal distributions is undertaken by a parametric bootstrapping method. With this approach, stochastic samples are generated from the log-Normal distribution fitted to historical maxima, and new log-Normal distributions are fitted to each synthetic data set; the quantiles obtained from these synthetic parameters are then used to provide an estimate of uncertainty in the flood quantiles. The steps involved in this approach are:

1. Use the log-Normal distribution obtained from fitting to the *N* maxima in the historic record to generate a sample of *N* synthetic flood maxima (using the parametric sampling approach described in Book 4, Chapter 4, Section 3)

2. Fit a log-Normal distribution to this synthetic sample (ie calculate the mean and standard deviations of the logs of this sample)

3. Repeat steps i) and ii) 100 times to obtain 100 sets of log-Normal parameters, where the 90% confidence limits of the parameters are determined simply by calculating the 5% and 95% exceedance percentiles of each sample.

The above steps are applied separately to the flood data available for the mainstream and tributary. The resulting distributions of the parameters are shown in Figure 7.9.4. It is seen that the uncertainties in the tributary parameters are slightly wider than those of the mainstream, which reflects the shorter record length (30 years versus 50).

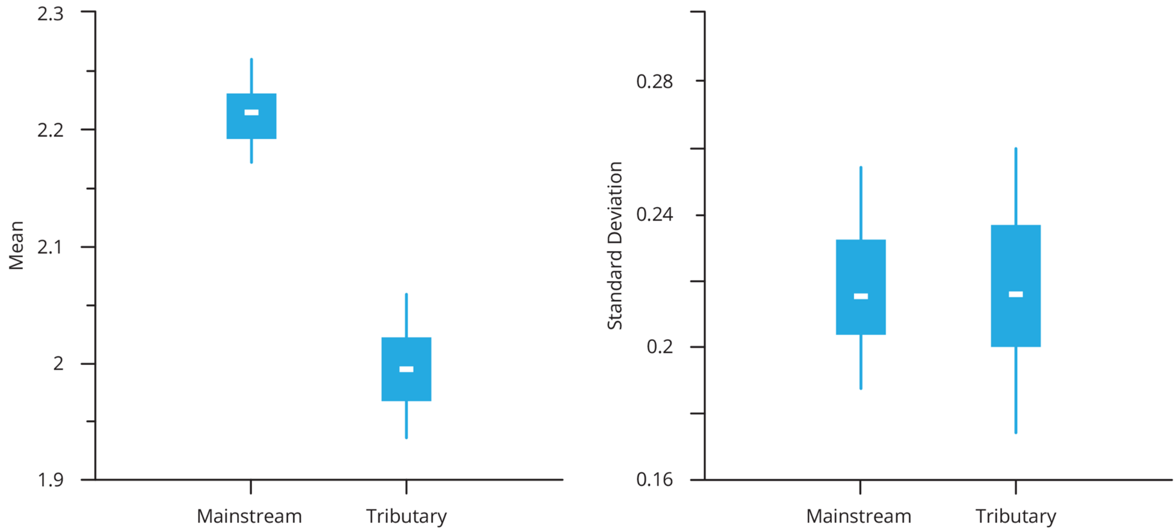

Figure 7.9.4. Uncertainty in parameters of the log-Normal distribution (high and low bars represent 5% and 95% limits, the high and low boxes represent 25% and 75% limits, and the central bar shows the median).

Uncertainty in correlation between flood maxima

The approach used to characterise uncertainty in the degree of correlation (*r*) between flood maxima in the two streams is similar to that used when errors are assumed to be Normally distributed (as described in Book 7, Chapter 9, Section 4). However, an additional transformation step is introduced to better conform to the assumed distribution of errors in estimates of the correlation coefficient (Fisher, 1915). Fisher's transformation of the correlation coefficient is approximately normally distributed with a mean (*r'*) and standard error (se'_r):

$$r' = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right) \quad (7.9.8)$$

$$se'_r = \frac{1}{\sqrt{N-3}} \quad (7.9.9)$$

The correlation between the log-transformed flood maxima in the two streams (*r*) is calculated to be 0.6, based on 30 years of concurrent data. The Fisher transformed estimates of *r'* and se'_r are thus calculated to be 0.693 and 0.192. With these calculated, the steps to generate a stochastic sample of correlations are as follows:

i. Generate a uniform random variate (*p*) between 0 and 1

ii. Compute the standard normal variate (*zi*) corresponding to *p*

iii. Obtain the quantile (g_i) corresponding to p from the inverse of the transformed normal distribution: $g_i = 0.693 + z_i 0.192$

iv. Apply the inverse of Fisher's transformation to g_i to obtain a stochastic estimate of the correlation coefficient (*ri*), where the inverse transform is calculated from the inverse of Equation (7.9.8):

$$r_i = \frac{e^{(2g_i)} - 1}{e^{(2g_i)} + 1} \tag{7.9.10}$$

v. Repeat steps i) to iv) 100 times to obtain a stochastic sample of correlation coefficients.

In this example, the mean of 100 correlation coefficients generated in this manner is found to be 0.603, where 90% of the sample is found to lie between 0.407 and 0.762.

Uncertainty in flood level estimates

A pragmatic approach is used to account for errors in the relationship between flows in the two streams and downstream flood levels. The approach is based on the simple assumption that the errors are normally distributed and invariant with magnitude, where the adopted standard deviation of the errors is 0.1m. The magnitude of the error term is based on the standard error of the regression relationship developed using hydraulic modelling, but this was increased slightly to reflect the additional uncertainty associated with the hydraulic modelling. The adopted approach could be modified to allow for errors in the slope of the fitted regression line and include dependency on flow magnitude, but this simpler approach provides a useful basis for exploring the sensitivity of the outcome to this source of uncertainty.

The steps involved in this are identical to that used in the preceding example in Book 7, Chapter 9, Section 4, as shown in Figure 7.9.3. An illustration of level estimates derived with the error term included is provided in Figure 7.9.5. The values on the x-axis correspond to the levels derived using the regression equation between upstream flows and levels simulated by the hydraulic model (Figure 4.4.15), and those on the y-axis include the normally distributed errors generated with a standard deviation of 0.1.

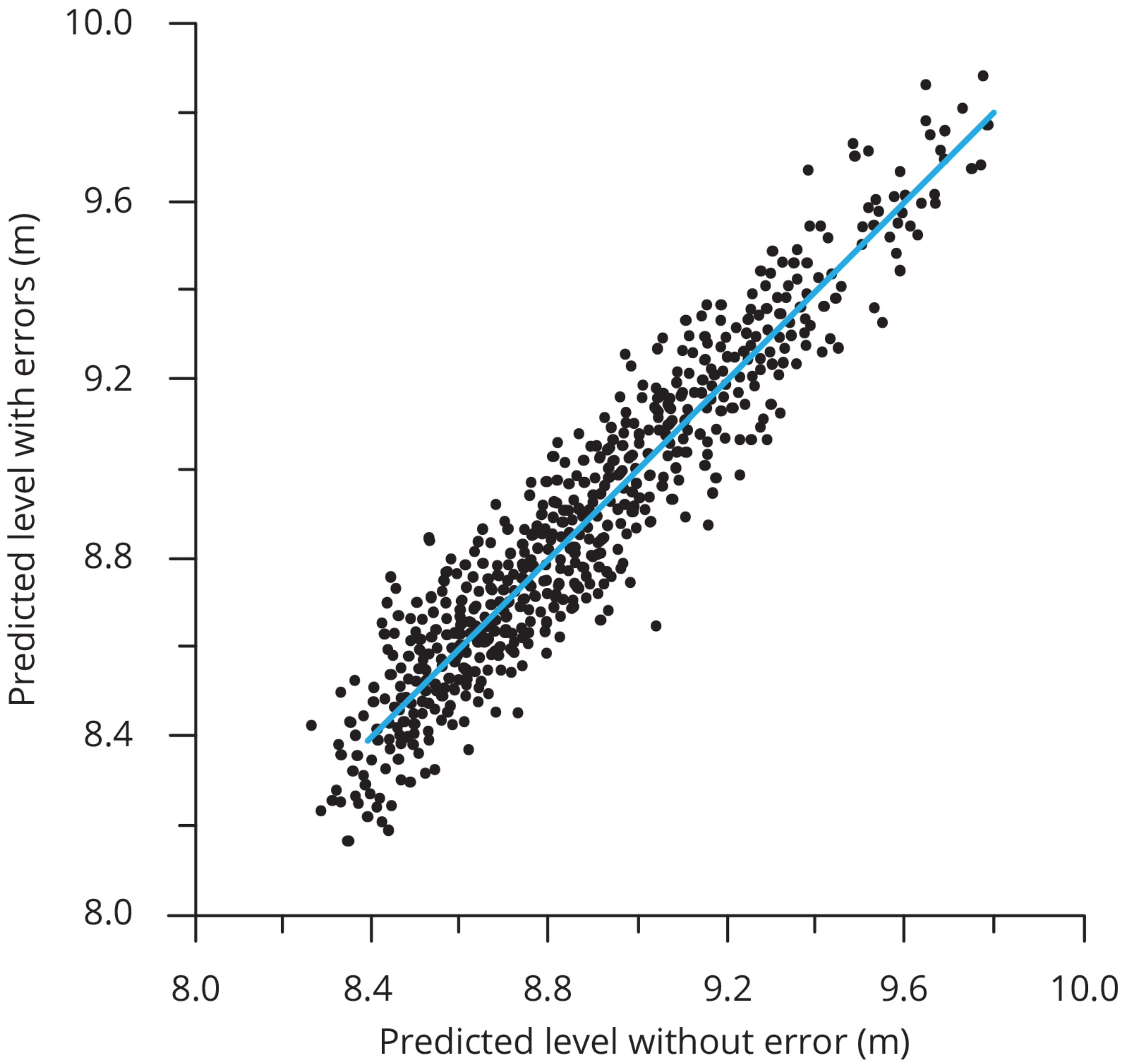

Figure 7.9.5. Uncertainty in levels estimated from the regression equation.

Uncertainty in derived level frequency curve

The final step required to assess the uncertainty in the derived frequency curve is to derive a frequency curve for each set of input parameters derived from the preceding three steps. That is, a flood level frequency curve is derived for the set of stochastic parameters generated in the preceding three steps, and the uncertainty in the design flood levels is obtained from the distribution of results.

The steps implemented to solve this using spreadsheet software are:

1. Generate 100 sets of stochastic parameters for the two log-Normal distributions and the correlation coefficient (this corresponds to step A in Figure 7.9.2)

2. For each set of parameters, generate 1000 stochastic samples of flood maxima in the mainstream and the tributary, using the procedure described in Table 4.4.1, then calculate the corresponding downstream flood levels from the regression relationship with a normally distributed error term added to the level estimates, as described above; these calculations correspond to steps B and C, shown in Figure 7.9.2.

3. Derive a flood level frequency curve by fitting a simple probability model to the 1000 stochastic maxima, as described in Table 4.4.1 (step D, Figure 7.9.2); this is used to estimate design levels for a range of exceedance probabilities.

4. Steps ii) and iii) are repeated for each of the 100 sets of stochastic parameters, which yields 100 estimates of design levels for each of the exceedance probabilities; these levels are ranked, and 90% of the range is used to represent uncertainty (step E, Figure 7.9.2).

The final level frequency curve and confidence limits derived using the above steps are shown in Figure 7.9.6.

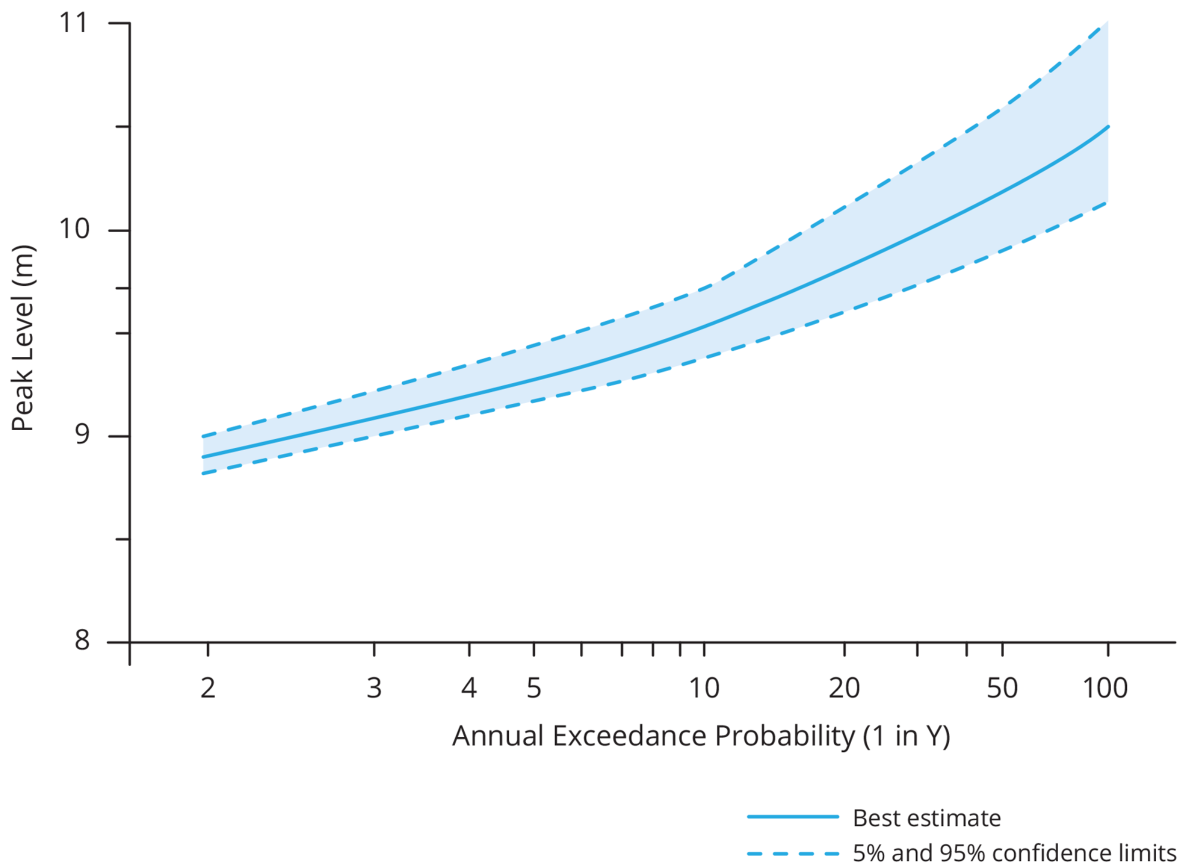

Figure 7.9.6. Confidence limits on the flood level frequency curve determined using the general framework for the analysis of uncertainty using Monte Carlo simulation.

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Chapter 10. Documentation, Interpretation and Presentation of Results

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Chapter Status	Final
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10.1. Introduction

Catchment modelling systems for flood estimation are applied to provide information to decision makers and designers on magnitudes and probabilities of flood characteristics, as a basis for decisions on flood-related planning, design and operations. The purpose, scope and required outputs of any flood investigation should be clearly described in the brief or technical specification for the design problem or flood study (NFRAG, 2014; McLuckie and Babister, 2015). It is therefore important that the client who commissions flood investigations should be comprehensive in the preparation of the brief to ensure that all requirements and objectives are covered in detail. The brief should be detailed but should not specify unrealistic objectives for the model performance. Unrealistic objectives may include over-optimistic calibration performance.

The results of any modelling should be documented and presented in a way that satisfies the requirements of the brief. However, even if such a brief or specification is not readily available, it is the responsibility of the modelling team to ensure that the modelling process is well documented and that the results are presented and communicated in a way that will be clearly understood by the target audience and will avoid any misinterpretation or misuse of the information. The documentation may need to cover requirements for several different audiences in particular circumstances, so it must be relevant for these audiences. In some cases, different reports may need to be prepared for these varied audiences.

10.2. Audience Considerations

Depending on the project and the specific requirements of the specification, the documentation should cater for the required audiences. Different audiences could include:

- *Client* - The client is the agency that has commissioned the flood report, and they will be seeking a report that outlines the whole scope of the report, especially covering the main issues required, as well as limitations and comments on accuracy and reliability. This report will be the basis for the client’s requirements, whether this is for planning, feasibility or design of infrastructure. The report should also clearly demonstrate the methodology and show that it was appropriate for the requirements, subject to the limitations of the specification. The client will also need to have a report that will be archived in their technical library and be available for reference in the future when the flood study may be reviewed or if later queries arise. All supporting data should also be archived by the client for future reference.

- *Regulatory or Approval Agencies* - Where the client is not itself a regulatory agency, these agencies need to be considered. For example, these may include agencies such as local authorities who need to consider impacts of projects on flood levels outside the project boundary, or environmental agencies who may need to understand any impacts on water quality or fauna movement. The report needs to demonstrate to these agencies that the flood study has been carried out to an acceptable technical standard and that their interests are satisfied.

- *Residents and the Public* - Local residents will take an interest in the findings of flood studies, particularly as they affect their individual interests. To meet their interests, the report should be written in plain English, though still to a high level of technical credibility, and should clearly outline the impacts on the local community and demonstrate that any adverse impacts have been mitigated or, if this proves impossible, demonstrate that all efforts have been made to minimise impacts.

- *Other Stakeholders* - These may include local community or environmental groups, who have no direct regulatory interest but who have a community interest in the results of the flood study. In this case, the report must be written in plain English but it must also be of a high technical standard, since these stakeholders will often have a high level of technical expertise.

10.3. Documentation

10.3.1. General

Documentation should be progressive through the different steps of a flood estimation study. The scope and level of detail of the documentation will depend to some degree on the nature of the modelling application but should be sufficient to provide the basis for an independent review of the modelling process and the results produced (DECC, 2007).

As discussed above the documentation needs to consider the requirements of the audience for the report, noting that there may be more than one audience. The documentation requirements outlined below apply to both the hydrologic and hydraulic modelling phases of a flood study. More detailed guidance on interpretation of the results of hydraulic modelling is provided in the ARR Project 15 report (Babister and Barton, 2016).

10.3.2. Data Collation and Quality Checking

The data used in the model development and study is the basis for the work, and a clear description and documentation of this data is essential for review and understanding of the process as well as for archiving and future reference. This documentation should cover all forms of data used from systematically recorded or surveyed data to informal sources of flood information, including historic records of rainfall, streamflow, flood level, flood extent data, topographic and survey data, as well as photographic and documentary information on floods (see Book 1, Chapter 4). It is recommended that the project report include a copy of the design input data downloaded from the ARR Data Hub (http://data.arr-software.org/) to aid in the reproducibility and review of results.

It is important that the process of data quality checking and the associated decisions are clearly recorded, as well as any assumptions or limitations. The documentation should clearly describe the approach to checking the data and indicate a descriptive understanding of the data quality and the impacts of this quality on the final outcomes of the project. To the extent that data ownership allows, a copy of the original data sets and the finally adopted data sets should be kept.

10.3.3. Model Development and Calibration

The documentation should cover all the stages of the model development, including the selection of the catchment modelling system, the key assumptions made in the model representation of the catchment or the flooded area, the selection of model parameter and design inputs, and the process used to ensure that the model is fit for the intended purpose. Key decisions made in this process should be clearly recorded. Comments on the parameter estimation process and the expected reliability of the results should also be included.

It is now quite common in flood study briefs to include as part of the study deliverables a requirement to provide a copy of the calibrated model (NFRAG, 2014). This should include the relevant information to allow a third party to run the model and review the modelling results. More details are provided in Babister and Barton (2016).

10.3.4. Modelling Results

Records of modelling results should include clear documentation of the scenarios, parameters and design inputs for the model runs. Electronic records of results should be in a format that allows ready processing for summaries and reports.

The modelling results should be supported by maps and graphs which can illustrate the procedures and methodology. Maps are an excellent means of allowing a comprehensive but easily understood interpretation of the results.

10.4. Interpretation of Modelling Results

10.4.1. Model Representation vs Reality

Hydrologic and hydraulic models are simplified representations of reality that are developed to allow assessment of flood problems, the final step in any form of modelling is therefore the interpretation of the modelling results in the light of the assumptions and simplifications made in the model formulation and any other limitations that might affect the modelling results. This can be seen as the reverse of the process of representing the real catchment and floodplain by a simplified, conceptualised model. The practitioner is in the best position to assess the impacts of the simplifications of the real system in terms of the uncertainties and potential bias introduced into the modelling results and it is thus the practitioner’s responsibility to communicate the results of this assessment.

10.4.2. Checking of Results

The documentation for studies should describe the checking of results that has been carried out. This checking covers a number of formal and informal processes and must ensure that the client and other readers have confidence in the conclusions and are satisfied that the model and results are as consistent as possible with reality. This checking can also assist clients in model applications and any limitations.

As discussed elsewhere in Australian Rainfall and Runoff, inaccuracies can result from a number of sources including:

- *Data Quality* - The quality of the hydrologic and hydraulic modelling depends on the quality of the local data used in the development and testing of the model.
- *Model Representation* - The model is a theoretical representation of reality and the quality of this representation should be indicated.

- *Model Extrapolation* - The model will be developed using certain available data for calibration or using regional parameter estimates. The application to design situations then requires extrapolation to larger floods or alternative catchment development scenarios. The quality of the model extrapolation into these alternative conditions should be reviewed.

All of these issues should be described in the study documentation.

The process for checking the performance of the model with these concerns will need to focus firstly on the basis of the model development and implementation. Secondary checks, which are equally important should focus on the results, where there are several approaches to checking.

Developing a process for checking that model results are sensible and consistent is a vital quality control measure for the practitioner. The practitioner needs to satisfy themselves that the model results are reasonable prior to publishing them in a report. The following is a checklist that the practitioner should consider when interpreting results:

- *Mass Balance* – errors greater than 1% to 2% should generally be investigated, and the cause of the errors identified and rectified where possible;

- *Runoff Volumes* – the total runoff as a percentage of rainfall volume should be determined and checked against typical runoff coefficients for similar catchments;

- *Runoff Rates* – can be used to check that the runoff rates predicted by the hydrologic model do not significantly diverge from runoff rates predicted by the hydraulic model. If divergence is significant, reason(s) for such should be determined.

- *Continuity* – discharge hydrographs should be obtained at several locations along each flow path, and at locations upstream and downstream of major flow path intersections, to check that the continuity and attenuation of flows is reasonable;

- *Stability* – the results should be checked for signs of instability, such as unrealistic jumps or discontinuities in flow behaviour, oscillations (particularly around structures or boundaries), excessive reductions in time step or iterations required to achieve convergence. Many models will specify criteria based on the Courant number (refer to Book 6) that can be checked to assess model instability;

- *Froude Numbers* – Froude numbers should be checked to identify areas of trans-critical and super-critical flow, and the implications of this flow behaviour on the model results considered. In general, model results in areas of trans-critical flow should be used with extreme caution. Flow over embankments, levees and other hydraulic control structures should be roughly checked with suitable hand calculations, such as the broad-crested weir equation;

- *Model Startup* – many models do not perform well from a completely “dry” start during the initial wetting stage. The practitioner should consider using a suitable “hot-start” condition if such functionality exists, or should exclude results from the very start of the model run from their analysis. This can be particularly important near structures;

- *Structure Head Losses* – head losses through structures such as bridges, culverts, siphons etc should be checked against suitable hand calculations. More discussion on how to deal with structures is presented in Book 6, Chapter 3. In particular, consideration should be made of the amount of expansion/contraction losses that are captured by the two dimensional schematisation, and whether the flow regime is adequately handled by the model; and

- *Steep areas/shallow flow* – it may be difficult to interpolate flow depths where steep shallow flow is occurring, particularly if the flow is not sub-critical. It may be necessary to check results against total energy calculations in such locations.

Results for similar projects in the vicinity should be reviewed to ensure that the results are consistent with these previous analyses. If there are differences, reasons for these differences should be sought and explained. If this is not the case, reconsideration of the model selection or implementation should be considered.

Alternative flood estimation methods, generally a simple regional method should also be considered again to check consistency. Again where there are inconsistencies, these should be investigated and reasons found for the differences.

These checks of results are important and increase confidence in the analysis. The flood study documentation should clearly outline this checking and demonstrate the level of confidence in the results.

10.4.3. Accuracy of Results

Book 1, Chapter 2, Section 8 gives information on the sources of uncertainty and Book 7, Chapter 9 of this book provides guidance on methods for determining uncertainty in modelling results. However, the formal sensitivity or uncertainty analysis will generally only cover the influence of the most important inputs and parameters on the modelling results. The practitioner thus needs to consider the likely magnitude of additional uncertainties introduced by secondary inputs and parameters.

The degree of scatter in results shown up by uncertainty analyses describes the *precision* of the flood estimate. However, the accuracy of modelling results depends also the degree of *bias* in the results (systematic underestimation or overestimation). Inappropriate representation of the real system by the adopted model is likely to introduce model errors (additional uncertainty and bias) into the modelling results, which are not captured by normal uncertainty analysis. The results of uncertainty analyses should thus be regarded as lower bound estimates of uncertainty.

An estimate of the likely model errors can be obtained by comparing results produced by different models of the same system or by comparison of flood estimates obtained by different flood estimation approaches.

The documentation must include sufficient discussion to allow the client and others who read the report (including non-experts) to understand the level of accuracy provided and to ensure that the report is not used to indicate a higher accuracy than can be justified by the model and the particular application of model calibration. To avoid misinterpretation, modelling results should be presented to the number of significant figures implied by accuracy considerations. Where there is uncertainty, this must be described clearly and understandably so that the client and others can make a reasonable decision on the results.

10.5. Presentation of Results

10.5.1. General

Depending on the nature and scope of the flood investigation, the modelling results may be presented in the form of a summary table of flood estimates, graphs, detailed reports, maps, audio-visual presentations or combinations of these elements. In all cases it is important that the form and detail of the presentation is directed at the target audience. Generally different forms and levels of presentation of study findings will be required for different stakeholder groups.

In addition to the summary of results, the documentation should include comments on the accuracy and reliability of the results. It should cover the basic discussion of calibration to historical flood events as well as extrapolation of the model to the design scenarios and to assessments beyond the scope of the calibration.

10.5.2. Qualifications and Caveats

The scenarios used in deriving the flood estimates need to be clearly stated, including the assumptions made with regard to climate and land use conditions, and possibly other system characteristics (e.g. operational conditions).

The modelling will have been developed for a specific application and therefore the model performance for other applications may be limited. This limitation could include the geographical extent as well as the flood magnitudes considered. For example, if the model has been developed for design of major infrastructure, it may be prepared for analysis of large floods, so the calibration may be inappropriate for small in-channel flows which may be required for another application.

The documentation therefore should clearly describe the limitations and the scope where the model results may be appropriate.

10.5.3. Use of Modelling Results in Decision Making

While the main interest of the stakeholders is mainly on ‘best estimates’ of the flood characteristics as the direct basis for flood maps and other regulatory instruments, reporting on the uncertainties attached to these ‘best estimates’ is important as a basis for decision making. This additional information and comments on the interpretation of the modelling results (Book 7, Chapter 9, Section 3) are essential inputs to risk assessment and risk management studies that will use the modelling results (Book 1, Chapter 5).

10.6. References

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