ARR

Australian Rainfall & Runoff

A GUIDE TO FLOOD ESTIMATION

BOOK 1 - SCOPE AND PHILOSOPHY

Version 4.2

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However, many of the practices recommended in the 1987 edition of ARR have become outdated, and no longer represent industry best practice.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.

Assoc Prof James Ball
ARR Editor

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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.

Change Log

Version 4.2 - Climate Change Chapter Update

In late 2022 the Australian Government Department of Climate Change, Energy, the Environment and Water in partnership with Engineers Australia commenced an 18 month project to update the climate change considerations chapter of the Australian Rainfall and Runoff guidelines (Chapter 6, Book 1) to incorporate the most recent and relevant climate science and projections. The project involved the undertaking of a rigorous literature review of hydroclimatology under climate change relevant to design flood estimation, which was peer reviewed and published in a leading international journal. The findings were used to draft practical flood guidance which was finalised after an extensive process of review and feedback by industry. Funding for this project was received from National Emergency Management Agency under the Disaster Risk Reduction Package. The project report was adapted to replace Book 1 chapter 6.

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This version updates Book 1 Chapter 6 to reflect updates in climate science as discussed above. While no other chapters have been updated some minor amendments were made to remove inconsistencies with the new chapter. FAQs relating to the update are available https://arr.ga.gov.au/contact-us.

Key updates in Version 4.2

Update	Version 4.2
Book 1	Book 1 Chapter 6 Climate change updated
Guideline formats	PDF Web-based version Epub version
User experience	FAQs added to Geoscience Australia Website
Climate change	Reflected best practice as of 2024 and IPCC 6
Other Minor Changes	List the minor changes to the following chapters for consistency Book 1 Chapter 4 Section 15.1 Book 1 Chapter 4 Section 16.1 Book 1 Chapter 5 Section 10.4 Book 2 Chapter 1 Section 3 Book 2 Chapter 3 Section 3 Book 6 Chapter 5 Section 5 Book 8 Chapter 7 Section 7 Book 9 Chapter 6 Section 4.2 Book 9 Chapter 6 Section 4.6

ARR 2019 (now Version 4.1)

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 was considered to be final.

ARR 2016 (now Version 4.0)

Released July 2016

BOOK 1

Scope and Philosophy

Scope and Philosophy

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Chapter 1. Introduction

James Ball, Mark Babister, Monique Retallick, Erwin Weinmann

Chapter Status	Final
Date last updated	14/5/2019

1.1. General

While previous editions of Australian Rainfall and Runoff have served the engineering profession and the general community well, in the period since the release of the previous edition, a number of developments have arisen that necessitate the production of a new edition. These developments include the many recent advances in knowledge regarding flood processes, the increased computational capacity available to engineering hydrologists, expanding knowledge and application of hydroinformatics, improved information about climate change and the use of stochastic inputs and Monte Carlo methods.

The intention during the development of this new edition has been to provide appropriate guidance addressing these issues. In many situations, the guidance provided in this edition of Australian Rainfall and Runoff requires an enhanced knowledge of flood generation and the design process. The guidance developed has maintained the aim of Australian Rainfall and Runoff which is to provide the best available information on design flood estimation in a manner suitable for use by Australian practitioners with varying levels of knowledge about the design flood problem, flood processes, and engineering hydrology.

Development of guidance for inclusion in Australian Rainfall and Runoff consistent with the aims previously stated poses the question of a definition for the design flood problem. Design flood estimation remains a problem for many engineering projects. Advice is required regarding design flood characteristics for the:

- design of culverts and bridges for cross drainage of transport routes;
- floodplain management and planning;
- design of urban drainage systems;
- design of flood mitigation levees and other flood mitigation structures;
- setting of flood planning levels; and
- design of dam spillways.

The flood characteristic of most importance depends on the nature of the problem under consideration, but typically it is one of the following:

- *Flow rate* - commonly the peak but other flood flows may be needed for particular projects;
- *Level* - commonly the peak but other flood levels may be needed for particular projects;
- *Volume* - the volume of flood hydrographs is required for the design of many hydraulic structures designed to retain part of the flood hydrograph for flood mitigation purposes;
- *Rate of rise* - needed for the planning associated with operation flood management such as preparation of evacuation routes; or

- *System failure* - this may be failure of a dendritic network within a catchment, the failure of a transport route crossing multiple catchments, or the failure of some other system due to the occurrence of one or more flood events.

While all of these flood characteristics have been noted as being of interest to flood practitioners, the dominant characteristic of concern, historically, has been the peak flood flow. The peak flood flow was also the main focus of the previous edition of Australian Rainfall and Runoff (Pilgrim, 1987).

In this edition of Australian Rainfall and Runoff, many of the recommended practices focus on the prediction of peak design flows and prediction of full hydrographs. Since publication of the last edition of Australian Rainfall and Runoff, it has been recognised that this focus on flows provided insufficient guidance on other flood characteristics. For the holistic planning, design and operation of flood management systems, flood characteristics other than peak flow will also be relevant. For example, the design flood storage for the many retarding basins located in urban areas is usually a flood volume issue rather than a peak flow issue. As a result, other recommendations in this edition of Australian Rainfall and Runoff focus on all flood characteristics that may be of interest in design flood estimation.

This approach is consistent with the aims of Engineers Australia's National Committee on Water Engineering when they resolved that a revision of Australian Rainfall and Runoff was needed by the profession and the wider community. These aims can be stated broadly as being:

- to collect, review and evaluate available design procedures, and to update the document to include the best available methods and design data Australia wide;
- to provide guidance to designers on procedures and design values to be used in design flood estimation;
- to provide guidance on the concepts involved in the recommended procedures and their application;
- to provide separate design information for individual regions where necessary;
- to provide guidance on design flood estimation under changing climatic conditions;
- to provide guidance on the likely accuracies, or uncertainty, in the application of the recommended techniques; and
- to carry out those research activities necessary to meet the above objectives.

In development of this guidance, 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 authorship 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. Assessment of the relative merits of new procedures and design information should be based on the following desirable attributes:

- based on observed data relevant to the specific application;
- consistent with current knowledge of flood processes;
- able to reproduce observed flood behaviour in the area of interest; and
- where possible, endorsed by a peer review process

While most of the procedures presented in the guidelines require software for their implementation, the role of Australian Rainfall and Runoff is not to endorse particular software packages but rather to provide details of the procedures to be incorporated in flood estimation software packages. However, enabling software is provided to allow site-specific design data to be extracted from databases (e.g. for the design rainfall database and the regional flood frequency estimation). These databases will be updated when warranted by the availability of significant amounts of new or revised information.

1.2. Contents

While the presentation and formats of Australian Rainfall and Runoff have varied between the editions, the focal aim has remained one of providing information relevant to design flood estimation in a form readily accessible to practitioners.

This edition of Australian Rainfall and Runoff has followed the same philosophy and has grouped information on different aspects of design flood estimation into separate books. The aim of this is to allow easy updating of components in the future. A total of 9 Books has been prepared for this edition of Australian Rainfall and Runoff with the following contents:

Book 1 - SCOPE AND PHILOSOPHY

This book provides a general introduction to Australian Rainfall and Runoff with an emphasis on the need for the revision and the basic philosophy for the application of the guidelines. It gives a brief introduction to terminology used within the document, discusses fundamental issues and basic approaches to flood estimation, data related aspects inclusive of its management and data uncertainty, risk based design and dealing with climate change.

Book 2 - RAINFALL ESTIMATION

This book discusses the importance of design rainfall for flood estimation, and includes discussion of differences between historical and design rainfalls, issues associated with development of rainfall models for design flood estimation in Australian Rainfall and Runoff. It provides the basis for the recommended Intensity Frequency Duration relationships, design spatial patterns of rainfall and design temporal patterns of rainfall. Also considered in this book are continuous sequences rainfall inclusive of the stochastic generation of alternative design storm sequences.

Book 3 - PEAK FLOW ESTIMATION

This book provides a general introduction to peak flow estimation based on flood frequency analysis, as well as covering specific technical aspects of this topic area. The first of the technical chapters provides guidelines for Flood Frequency Analysis at a specific site, illustrated by a range of examples. The second deals with Regional Flood Frequency Estimation techniques and describes the application of a tool developed to readily provide peak flow frequency estimates for any location in Australia.

Book 4 - CATCHMENT SIMULATION FOR DESIGN FLOOD ESTIMATION

This book deals with general concepts and issues in catchment modelling for design flood estimation. The first chapter discusses the need for catchment simulation and introduces general catchment simulation concepts. The next chapter discusses key hydrologic processes contributing to floods and how they are represented in modelling systems. This chapter is followed by a discussion of the types of catchment modelling systems (event and continuous) and the need for integrating hydrologic, and hydraulic components of the system. The final chapters deal with the treatment of joint probability issues and uncertainty in the outputs of simulation models.

Book 5 - FLOOD HYDROGRAPH ESTIMATION

The focus of this book is the hydrologic models necessary for prediction of design flood hydrographs. The first chapter gives a general introduction to concepts presented in this book while the remaining chapters deal with the modelling of particular components of the flood formation process. The first of the technical chapters deals with the different types of hydrologic models used to represent the runoff generation and runoff routing phases of the flood formation process. The final two chapters deal with baseflow and losses for design flood estimation and provide design data for these important inputs to flood hydrograph estimation.

Book 6 - FLOOD HYDRAULICS

This book is concerned with the basic aspects of hydraulics. It is worth noting that the material presented in this chapter is not a replacement for the many textbooks in this area or that it will cover all the information necessary for the application of hydraulic principles in design flood estimation. The chapters in this book present information relevant to the hydraulic modelling of river reaches, floodplains and structures for design flood estimation, the application of software for numerical modelling of flood hydrographs, blockage of hydraulic structures and interaction of coastal and catchment flooding. A tool has been developed to assist practitioners in assessing the interation of coastal and catchment flooding. Also included in this book is guidance on designing for the safety of people and vehicles. The people safety information presented includes a discussion of the importance of the demographics in assessing safety.

Book 7 - APPLICATION OF CATCHMENT MODELLING SYSTEMS

This book provides discussion of major issues in the practical application of catchment modelling systems to different flood estimation problems, including establishment of catchment modelling systems, calibration and validation of model parameters and dealing with uncertainty in model outputs.

Book 8 - VERY RARE TO EXTREME FLOOD ESTIMATION

This book provides information and guidelines for the special design applications where floods of low Annual Exceedance Probabilities need to be estimated. Examples of these design applications include the sizing of spillways for large dams, design of major structures located in the floodplain and flood risk management in situations where very large flood damages or significant risk to life from flooding could be expected. Floods in the range of very rare to extreme events are generally estimated by the methods described in Book 8, Chapter 2 to Book 8, Chapter 7 but a number of special considerations and additional design data are required, as described in Book 8. This book includes an overview of the procedures available for estimating very rare to extreme floods, estimation of design rainfall and rainfall excess for rarer events, and special requirements for the models used to generate flood hydrographs for very rare to extreme flood events. The application of these special procedures is illustrated by a number of examples.

Book 9 - RUNOFF IN URBAN AREAS

This book first provides a general introduction to urban drainage systems and the philosophy adopted in Australian Rainfall and Runoff. It then discusses urban drainage approaches, changes to the natural hydrologic cycle resulting from urbanisation and how these changes impact on design flood estimation in urban environments, and use of storage facilities from on-site storage to detention (retention) basins to large flood mitigation dams. An important aspect of this discussion relates to limitations of the Rational method and the changes in approach necessary for consideration of volume-based problems rather than peak flow based problems.

1.3. References

Pilgrim, DH (ed) (1987) Australian Rainfall and Runoff - A Guide to Flood Estimation, Institution of Engineers, Australia, Barton, ACT, 1987.

Chapter 2. Fundamental Issues

James Ball, Mark Babister, Monique Retallick, Fiona Ling, Mark Thyer

Chapter Status	Final
Date last updated	14/5/2019

2.1. Introduction

This chapter introduces important concepts of probability and statistics with respect to flood estimation, and defines the recommended terminology for these probability concepts. The chapter also discusses the difference between design and actual events, conversion of rainfall of a given probability to a flood of the same probability, risk-based design and dealing with uncertainty in flood estimates. Much of the text from the 1987 edition of Australian Rainfall and Runoff is still relevant and has formed the basis for the information provided in some of following sections.

2.2. Terminology

2.2.1. Background

Probability concepts are fundamental to design flood estimation and appropriate terminology is important for effective communication of design flood estimates. Terms commonly used in the past have included "*recurrence interval*", "*return period*", and various terms involving "*probability*". It is common for these terms to be used in a loose manner, and sometimes quite incorrectly. This has resulted in misinterpretation by the profession, the general community impacted by floods, and other stakeholders.

In considering the terminology that should be used in this edition of Australian Rainfall and Runoff, the National Committee on Water Engineering's three major concerns were:

- Clarity of meaning;
- Technical correctness; and
- Practicality and acceptability.

2.2.2. Clarity of Meaning

Use of the terms "*recurrence interval*" and "*return period*" has been criticised as leading to confusion in the minds of some decision-makers and members of the public. Although the terms are simple superficially, they are misinterpreted regularly as implying that the associated event magnitude is only exceeded at regular intervals, and that they are referring to the expected elapsed time till the next exceedance. This misinterpretation of the terms used for expressing probabilities of flood magnitudes can be misleading and result in poor decisions.

It is believed that irrespective of the terms used, it is critical that all stakeholders have a common interpretation of the terms. Furthermore, it is important that stakeholders understand that the terms refer to long term averages. This means, for a given climatic environment, that the probability of an event of a given magnitude being equalled or exceeded in a given period of time (for example, one year) is unchanged throughout the life of the structure or the drainage network. Furthermore, it is not uncommon for an event to occur more than once in a single year.

Additionally, given the wet and dry phases that occur in many regions of Australia, these events are likely to be clustered in time. The occurrence of these wet and dry climatic phases highlight the misleading and inappropriate interpretation that flood events occur at regular intervals as implied by "*recurrence interval*" and "*return period*".

Flood events generally are random occurrences, and the period between exceedances of a given event magnitude usually is a random variate, the properties of which are assumed to be constant in time for a given location and climatic environment. The adopted terminology reflects this fundamental concept and is intended to convey a clear and precise interpretation.

2.2.3. Technical Correctness

In view of the loose and frequently incorrect manner in which probability terms are often used, it was considered that Australian Rainfall and Runoff should adopt terminology that is technically correct, as far as this is possible and in harmony with other objectives. Additionally, even if this is not entirely popular with all practitioners, Engineers Australia has a responsibility to encourage and educate engineers regarding correct terminology.

The two approaches used when describing probabilities of flood events in previous editions of Australian Rainfall and Runoff were:

- *Annual Exceedance Probability (AEP)* - the probability of an event being equalled or exceeded within a year. Typically the AEP is estimated by extracting the annual maximum in each year to produce an Annual Maxima Series (AMS); and
- *Average Recurrence Interval (ARI)* - the average time period between occurrences equalling or exceeding a given value. Usually the ARI is derived from a Peak over Threshold series (PoTS) where every value over a chosen threshold is extracted from the period of record.

Details of AMS and PoTs and the background to these alternative techniques for extracting flood series from recorded data are presented in Book 3, Chapter 2. Included in this discussion are the assumptions necessary for conversion of one probability terminology to the other using the Langbein formula (Langbein, 1949).

Using the Langbein formula, in probability terms, there is little practical difference for events rarer than 10% AEP. Historically, however, there has been a reluctance to convert from the approach used for derivation of the design flood estimate. Furthermore, terminology was attached to particular design flood estimation techniques; for example, when AMS were used to derive design flood estimates, the resultant probability was expressed as an AEP while when a PoTS was used for the same purpose, the resultant probability was expressed as an ARI.

In many situations, this distinction between an ARI and an AEP was imprecise as the design flood prediction methodology adopted did not explicitly note the use of either an AMS or a PoTS in the methodology. As a result, use of ARI and AEP was considered to be interchangeable. This interchangeable use often resulted in confusion.

The National Committee on Water Engineering believes that within Australian Rainfall and Runoff a terminology should be used which, while being technically correct, is consistent with other uses. Furthermore, the terminology adopted should be easily understood both by the profession and by other stakeholders within the community.

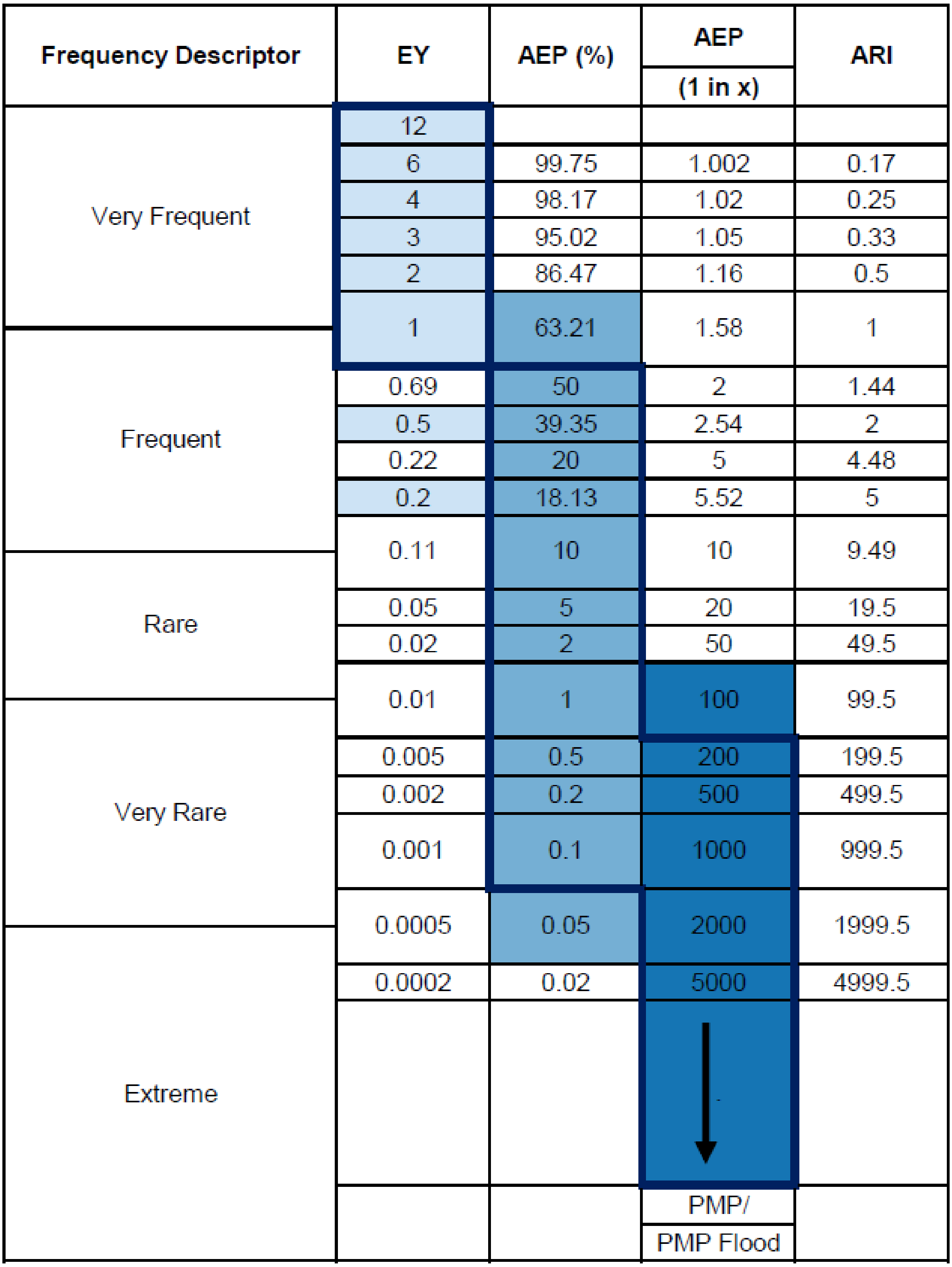
2.2.4. Practicality and Acceptability

The National Committee on Water Engineering is aware that while the terminology adopted must be technically correct it must also be relatively simple and suitable for use in practice. Terminology that meets this criterion will be accepted by the profession and by other stakeholders.

The interaction of the profession with the community and the increased public participation in decision making means that terminology needs to be clear not only to the profession but also to the community and other stakeholders, other professions involved in flood management, and to the managers of flood-prone land. This need has resulted in a move away from the terminology adopted in the 1987 Edition of Australian Rainfall and Runoff towards a clear and unambiguous terminology supported by the National Committee on Water Engineering of Engineers Australia and the National Flood Risk Advisory Group (NFRAG, a reference group under the Australian and New Zealand Emergency Management Committee). All parties believe that terminology involving annual percentage probability best conveys the likelihood of flooding and is less open to misinterpretation by the public.

2.2.5. Adopted Terminology

To achieve the desired clarity of meaning, technical correctness, practicality and acceptability, the National Committee on Water Engineering has decided to adopt the terms shown in Figure 1.2.1 and the suggested frequency indicators.



Frequency Descriptor	EY	AEP (%)	AEP (1 in x)	ARI
Very Frequent	12			
	6	99.75	1.002	0.17
	4	98.17	1.02	0.25
	3	95.02	1.05	0.33
	2	86.47	1.16	0.5
	1	63.21	1.58	1
Frequent	0.69	50	2	1.44
	0.5	39.35	2.54	2
	0.22	20	5	4.48
	0.2	18.13	5.52	5
	0.11	10	10	9.49
Rare	0.05	5	20	19.5
	0.02	2	50	49.5
	0.01	1	100	99.5
Very Rare	0.005	0.5	200	199.5
	0.002	0.2	500	499.5
	0.001	0.1	1000	999.5
	0.0005	0.05	2000	1999.5
Extreme	0.0002	0.02	5000	4999.5
			↓	
			PMP/	
			PMP Flood	

Figure 1.2.1. Australian Rainfall and Runoff Preferred Terminology

Navy outline indicates preferred terminology. Shading indicates acceptable terminology which is depends on the typical use. For example in floodplain management 0.5% AEP might be used while in dam design this event would be described as a 1 in 200 AEP.

As shown in the third column of Figure 1.2.1, the term Annual Exceedance Probability (AEP) expresses the probability of an event being equalled or exceeded in any year in percentage terms, for example, the 1% AEP design flood discharge. There will be situations where the use of percentage probability is not practicable; extreme flood probabilities associated with dam spillways are one example of a situation where percentage probability is not appropriate. In these cases, it is recommended that the probability be expressed as 1 in X AEP where 100/X would be the equivalent percentage probability.

For events more frequent than 50% AEP, expressing frequency in terms of annual exceedance probability is not meaningful and misleading , as probability is constrained to a maximum value of 1.0 or 100%. Furthermore, where strong seasonality is experienced, a recurrence interval approach would also be misleading. An example of strong seasonality is where the rainfall occurs predominately during the Summer or Winter period and as a consequence flood flows are more likely to occur during that period. Accordingly, when strong seasonality exists, calculating a design flood flow with a 3 month recurrence interval is of limited value as the expectation of the time period between occurrences will not be consistent throughout the year. For example, a flow with the magnitude of a 3 month recurrence interval would be expected to occur or be exceeded 4 times a year; however, in situations where there is strong seasonality in the rainfall, all of the occurrences are likely to occur in the dominant season.

Consequently, events more frequent than 50% AEP should be expressed as X Exceedances per Year (EY). For example, 2 EY is equivalent to a design event with a 6 month recurrence interval when there is no seasonality in flood occurrence.

Different users of Australian Rainfall and Runoff, in general, will use different segments of the relationship between flood magnitude and exceedance probability. To reduce confusion, that may arise from switching between different terminologies, it is recommended that consistent terminology in accordance with one of the columns of Figure 1.2.1 be used within an industry segment.

These expressions of estimated frequencies relate directly to the particular time period for which data have been analysed and frequencies determined with no consideration given to the long term effects of climatic change. Nonetheless, the adopted terminology is considered to be equally applicable to both stationary and non-stationary climatic environments, as there is no requirement for the annual exceedance probabilities to be constant over time. Consequently, where flood characteristics are changing as result of long term climatic change, the AEP of a flood characteristic for a future time period may be different or, conversely, a flood characteristic magnitude corresponding to a given AEP may change.

2.3. Difference Between Design Events and Actual Events

Much confusion has resulted from lack of recognition of the fundamental differences between these two types events and associated of flood estimation problems. Although the same mathematical procedures may be involved in both cases, the implications and assumptions involved, and the validity of application, are quite different. The emphasis in this document is largely on design floods.

A design flood is a probabilistic or statistical estimate, being generally based on some form of probability analysis of flood or rainfall data. An Annual Exceedance Probability is attributed to the estimate. This applies not only to normal routine design, but also to probable maximum estimates, where no specific probability can be assigned but the intention is to obtain a design value with an extremely low probability of exceedance. In the flood estimation methods based on design rainfalls, the probability relationship between design rainfall events and design flood events is not a direct one. Occurrence of a rainfall eventwhen the catchment is wet might result in a very large flood, while occurrence of the same rainfall event when the catchment was dry might result in relatively little, or even no runoff. For the design situation, the combinations of different factors combining to produce a flood event are not known and must be assumed, often implicitly in the design values that are adopted.

The approach to estimating an actual (or historic) flood from a particular rainfall event is quite different in concept and is of a deterministic nature. All causes and effects are directly related to the specific event under consideration. The actual antecedent conditions prevailing at the time of occurrence of the rain are directly reflected in the resulting flood and must be allowed for in its estimation. No real information on the probability of the on flood probability can be gained from consideration of a single actual flood event.

Although the differences in these two types of events are often not recognised, they have three important practical consequences. The first is that a particular procedure might be might be appropriate for analysing actual flood events but quite unsuitable for probabilistic design flood events.

The second concerns the manner in which values of parameters are derived from recorded data, and the manner in which designers regard these values and apply them. If actual floods are to be estimated, values for use in the calculations should be derived from calibration on individual observed events. If design floods are to be estimated, the values should be derived from statistical analyses of data from many observed floods.

The third practical consequence concerns the manner in which parameters are viewed by designers and analysts. For example, design initial losses for bursts can be very different from event initial losses derived from actual events, yet practitioners still often compare them without understanding the differences.

2.4. Probability Concepts

2.4.1. Probability Relationship Between Design Rainfall and Design Flood Characteristics

In the flood frequency based design flood estimation approaches covered in Book 3, the probabilities of a specific event magnitude being equalled or exceeded are estimated directly for the flood characteristic of interest (e.g. peak flow or flood volume). However, for the catchment simulation and hydrograph estimation procedures covered in Book 4, Book 5 and Book 7, the exceedance probability associated with design rainfall, as the primary probabilistic input to the design flood estimation procedure, needs to preserved in its transformation to a design flood. This concept is often referred to as AEP neutrality.

However, each of the processes represented in a model that converts rainfall to runoff and forms a flood hydrograph at the point of interest introduces some joint probability, resulting in the fundamental problem that the true probability of the derived flood characteristic may be obscure, and its magnitude may be biased with respect to the true flood magnitude with the same probability as the design rainfall, especially at the low probabilities of interest in design.

Since publication of ARR 1987 (Pilgrim, 1987) there has been a steady shift towards methods that better account for the stochastic nature of how floods of different magnitude and exceedance probabilities are generated. Procedures of different complexity to deal with this fundamental issue are discussed in Book 1, Chapter 3.

2.4.2. Choosing a Quantile Estimator

The 1 in Y AEP quantile corresponds to the flood magnitude with annual probability of exceedance equal to 1/Y. Because the parameters of the flood frequency distribution have to be estimated from limited data, the true quantile is not known. Different quantile estimates are available depending on the application. These are described in Book 3, Chapter 2.

In cases where the interest is principally on the accurate estimation of the AEP that corresponds to a specified flood magnitude (e.g. the flood level at which a particular flood protection structure is expected to fail), an expected AEP (or expected probability) quantile should be used. The use of such a quantile ensures that, on average, its AEP equals the true value. In cases where the mean-squared-error in the flood magnitude is to be minimized for a given AEP, expected parameter quantiles should be used.

The difference between these quantile estimates is typically not of significance when there is little or no extrapolation of the observed range of data, and especially if the skew is small. However, if extrapolation is required and high skews are involved, the difference can be appreciable. The methods in Book 3, Chapter 2 describes how to estimates these quantiles.

2.4.3. Avoiding Inconsistencies in Procedures and Resolution

The important step often overlooked by practitioners is mistakenly using an input or parameter that was derived a particular way and at a particular resolution in a manner that is different to how it was derived. This is particularly difficult to avoid with digital data sets compiled from different sources and resolutions. Historically problems have arisen when a method was derived from one scale map and used at a different scale.

2.5. Risk-Based Design

Floods can cause significant impacts where they interact with the community and the supporting natural and built environment. However, flooding also has the potential to be the most manageable natural disaster as the likelihood and consequences of the full range of flood events can be understood, enabling risks to be assessed and where necessary managed. There is strong move from managing floods by a by simple standards approach, where a certain frequency of flooding is deemed acceptable, to risk-based approaches, where the consequence and probability of design capacity being exceeded are assessed explicitly. Risk and design flood estimation concepts are discussed in detail in Book 1, Chapter 5.

2.5.1. Route Serviceability

A particular aspect of risk based approaches is where total system risk is of main interest. With a railway or major road, flooding of any one of many stream crossings will cause closure of the route. The item of real interest is the probability of this closure, and not of failure at any particular site. This probability of closure will be much greater than that at an individual site. Closure of the route at any site may cause major disruption and economic losses. Upgrade works can be targeted at reducing the probability of closure.

This problem is receiving increasing attention from transport managers and is discussed in detail in Book 1, Chapter 5.

2.6. The Importance of Data

Data is fundamental to flood estimation. Data is needed to understand the processes involved in the formation of floods and to ensure that models are accurate and reflect the real world issues being analysed. Flood estimation primarily uses data that describes the rainfall, streamflow and water levels. The procedures and guidelines presented in ARR could not have been developed without historical data, and often the reliability of the methods presented depends on the extent of data that has been used in development.

For the first time, ARR has been based completely on Australian data to better reflect Australia’s variable landscape, including a national database of extreme flood hazards. A major task of the current ARR update was assembling a national databases of rainfall and streamflow data for developing inputs and methodologies. ARR 1987 (Pilgrim, 1987) used 600 pluviographs rainfall gauge (measures the amount of rainfall which fell) with greater than 6 years data and 7500 daily rainfall gauges with over 30 years record. ARR 2016 uses almost 30 years of extra rainfall and streamflow data, including data from over 2200 pluviographs and over 8000 daily rainfall gauges. Over 900 streamflow gauges were analysed. Over 100, 000 storm events were analysed. This data provides a valuable resource for the development of future methodologies.

Major improvements have been made to design flood estimation methods but national databases will allow the use and parameterisation of more complex methods. Major advances will continue that will allow us to leverage the limited data we can afford to collect on the continent nation. Many projects have opened the eyes of researchers and practitioners on what could be done with more time, money and the still limited data available. The data sets developed as part of this update should be enhanced and applied to for future improvements.

Book 1, Chapter 4 provides a summary of the types of data used for flood estimation.

2.7. Climate Change

ARR 1987 (Pilgrim, 1987) while acknowledging climate change did not address climate change or non-stationarity or provide guidance on the inclusion of climate change impacts in flood estimation. One key aim of this edition was the incorporation of the best available information of climate change impacts on flooding.

This edition of ARR funded research projects which investigated the following aspects:

- How climate change will affect flooding and the factors influencing flooding;
- How to incorporate climate change into the investigation methodologies used by the engineering profession to estimate design floods;
- Updating of the methodology in Australian Rainfall and Runoff so that the outcomes from climate change research (e.g. regional dynamic downscaling) can be incorporated easily into the investigation methodology as the science and results become available.

The impacts of climate change on design flood estimation are discussed in detail in Book 1, Chapter 5, Section 10. More detail can be found in the ARR Climate Change Research Plan and ARR Project 1: Climate Change Synthesis report (Bates and Westra, 2013; Bates et al., 2015).

2.7.1. Climate Change Impacts on Flooding

Global warming has been observed over several decades, and has been linked to changes in the large-scale hydrological cycle including increasing atmospheric water vapour content; changing precipitation patterns, intensity and extremes; changes in soil moisture and runoff; and increasing melting of snow and ice (Bates et al., 2008).There is increasing evidence that human-induced climate change is changing precipitation extremes, and that extreme flooding globally has increased over the 20th century (Trenberth, 2011). There is confidence that these changes in the hydrological cycle will lead to increased variability in precipitation and increased frequency of flood events over many areas (IPCC, 2007; Bates et al., 2008). Changes in climate will result in changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and may lead to unprecedented extreme weather and climate events (IPCC, 2012).

The major areas where climate change will impact flooding are:

- Design rainfall intensity-frequency-duration;
- Storm type, frequency, and depth;
- Rainfall spatial and temporal patterns;
- Antecedent conditions;
- Changes in sea level; and
- The joint probability of storm surge and flood producing rainfall.

2.7.1.1. Climate Change Impacts on Rainfall

Changes in extremes events, such as floods, can be linked to changes in the mean, variance, or shape of probability distributions, or all of these (IPCC, 2012). For example, climate change projections have shown that a relatively small shift in the distribution of precipitation may result in a large change in the frequency and magnitude of extreme precipitation events (Nicholls and Alexander, 2007). Studies have shown that a change in the shape of the distribution of precipitation is likely to have a greater effect on the frequency of extremes than a shift in the mean precipitation (White et al, 2010; Groisman et al., 1999), and that climate change is most likely to increase climate variability, particularly affecting the extremes (Jones et al., 2012; Fowler and Ekstrom, 2009).

A warming climate leads to an increase in the water holding capacity of the air, which causes an increase in the atmospheric water vapour that supplies storms, resulting in more intense precipitation. This effect is observed, even in areas where total precipitation is decreasing (Trenberth, 2011). Indeed, some of the largest impacts of climate change are likely to result from a shift in the frequency and strength of climatic extremes, including precipitation (White et al, 2010). It is likely that the frequency of heavy precipitation will increase by the end of the 21st century, particularly in the high latitudes and tropical regions and there is likely to be an increase in heavy rainfalls associated with tropical cyclones (IPCC, 2012).

There have been many studies globally that have found increases in the intensity or frequency of extreme precipitation events (Bates et al., 2008; Westra et al., 2013). It is likely that since the 1970s the frequency of heavy precipitation events has increased over most areas (Bates et al., 2008). From 1950 to 2005, extreme daily rainfall intensity and frequency has increased in north-western and central Australia and over the western tablelands of New

South Wales, but decreased in the south-east and south-west and along the central east coast (CSIRO and Australian Bureau of Meteorology, 2007). Projections analysed by CSIRO and Australian Bureau of Meteorology (2007) showed that an increase in daily precipitation intensity is likely under climate change. The study found that the highest 1% of daily rainfalls tends to increase in the north of Australia and decrease in the south, with widespread increases in summer and autumn, but not in the south in winter and spring when there is a strong decrease in mean precipitation (CSIRO and Australian Bureau of Meteorology, 2007).

The increases in precipitation are more evident in sub-daily rainfalls and major changes in the intensity and temporal patterns of sub-daily rainfalls can be expected by the end of the 21st century (Westra et al., 2013). In a study of downscaled outputs from climate models, Abbs and Rafter (2008) found that by 2070 the models projected an increase of an average of 40% in intensity for 24 and 72 hour events around the Queensland-New South Wales border, and an increase of more than 70% in the two hour rainfall events in the high terrain inland from the Gold Coast.

2.7.1.2. Antecedent Conditions

Changes in the patterns of precipitation and in evaporation will lead to changes in antecedent conditions prior to flood events, affecting soil moisture and thus loss rates in the catchment (Bates et al., 2008). Potential evaporation is projected to increase almost everywhere on a global scale due to an increase in the water-holding capacity of the atmosphere with higher temperatures combined with little projected change in relative humidity (Bates et al., 2008).

Projections of potential evapotranspiration over Australia show increases by 2030 and 2070. The largest projected increases are in the north and east, where the change by 2030 ranges from little change to a 6% increase, with the best estimate being a 2% increase. By 2070, the A1FI scenario gives increases of 2% to 10% in the south and west with a best estimate of around 6%, and a range of 6% to 16% in the north and east with a best estimate around 10% (CSIRO and Australian Bureau of Meteorology, 2007).

Projected decreases in rainfall over much of Australia combined with increases in evaporation may result in disproportionate decreases in runoff due to a disconnection between surface and groundwater, as was experienced in parts of Australia during the Millennium drought (CSIRO, 2012).

2.7.1.3. Sea Level

The relatively small rise in sea level that is seen in observed data over the past century has already caused a significant change in the frequency of extreme sea-level events, and associated flooding (Hunter, 2007). Studies of observed sea level data worldwide have shown that sea level rise is the predominant cause of increases in the frequency of extreme sea level events (IPCC, 2007; Hunter, 2007). There is high confidence that there has been an increase in the frequency of high coastal sea level events of a given magnitude, and that extreme flooding events due to sea level rise will increase significantly, dependent on location (Church et al., 2012). The likely range of global-mean sea level rise between the 1980 – 1999 and 2090 – 2099 periods is given by (IPCC, 2007) as 0.18 – 0.59 m. There is high confidence that the global rate of sea level rise has increased between the mid-19th and the mid-20th centuries. The average rate was 1.7 ± 0.5 mm/yr for the 20th century and 3.1 ± 0.7 mm/yr for 1993–2003 (Bates et al., 2008). The observed rate of sea level rise in the Australian region from 1993 - 2011 has high spatial variability, with a maximum in the north and north-west coasts of Australia of 9mm/yr, and a rate of 2 to 4 mm/yr on the south-eastern and eastern Australian coastline (Church et al., 2012).

2.8. Dealing with Uncertainty

2.8.1. Introduction

This section provides an overview of the uncertainties in the design flood estimation. The specific aims are to:

- Identify the types of uncertainty in design flood estimation;
- Motivate practitioners on the value of undertaking uncertainty analysis; and
- Raise awareness of the various sources of uncertainty in common techniques for design flood estimates.

2.8.2. Types of Uncertainty in Design Flood Estimation

It is typical in current practise for design flood estimation to ignore the uncertainty in the estimates of the design flood. This is despite the considerable uncertainties that are introduced when undertaking a Flood Frequency Analysis using short data records and extrapolating the fitted flood frequency distribution to estimate the 1% or 0.5% Annual Exceedance Probability flood. Similarly, when using a catchment modelling approach to obtain estimates of the design flood, the typical situation is that the catchment modelling system is calibrated to data from a few selected flood events, and the calibrated model is then extrapolated using design rainfall estimates (which itself is an extrapolation of observed rainfall data, Book 2, Chapter 3) to provide estimates of the 1% or 0.5% Annual Exceedance Probability flood. Both these type of approaches introduce significant uncertainties in estimates of the design flood.

The causes of these uncertainties are that practitioners are required to: (1) Use mathematical algorithms to represent the complexity of catchment processes that transform rare rainfall into rare flood events. (2) Calibrate and validate these algorithms using measurements of the catchment process that are highly uncertain. It is widely acknowledged that there is significant spatial variation in catchments and temporal and spatial variation in the antecedent catchment wetness and rainfall events that drive significant flood events. Practitioners use hydrologic models, which are simplified mathematical conceptualisations to represent these complex spatially and temporally distributed hydrological processes. These hydrologic models are calibrated to measurements of data on variables such as rainfall, evaporation and flow. It is widely acknowledged that these data can have significant measurement errors (refer to Book 1, Chapter 4). Rainfall is spatially heterogeneous, however, typically there are only a small number rainfall gauges in a given catchment. Streamflow is based on river height (stage) measurements and a rating curve, which can be difficult to reliability estimate for large flood events. Typically these uncertainties are ignored in the design flood estimation process.

Uncertainty analysis provides the tools with which to handle this uncertainty and incorporate it into the design flood estimates. To enable the use of uncertainty analysis tools, it is first important to distinguish two broad types of uncertainty:

- *Aleatory (or inherent) Uncertainty* - refers to uncertainty that arises through natural randomness or natural variability that we observe in nature; and

- *Epistemic (or knowledge-based) Uncertainty* - refers to uncertainty that is associated with the state of knowledge of a physical system (our estimation of reality), our ability to measure it and the inaccuracies in our predictions of the physical system.

These definitions are consistent with the broad definitions provided by Ang and Tang (2007) in wider context of general engineering and the specific context of flood risk by Pappenberger and Beven (2006). The major differences between the two types of uncertainty is that epistemic uncertainty can be reduced, through advances in process understanding or improvement in measurement techniques, while aleatory uncertainty cannot be reduced, and therefore needs to be characterised. Both types of uncertainty can be characterised using tools of uncertainty analysis. Ang and Tang (2007) provide a wealth of examples of the two types of uncertainty in a general engineering context.

In the context of design flood estimation, a simple example to understand the differences between these two types of uncertainty is to consider an example of a flood frequency distribution, as shown in Figure 1.2.2, with probability limits on the design flood estimates over the range of Annual Exceedance Proabilities.

An illustration of aleatory uncertainty is the natural variability in annual maximum floods which is due to the climate variability in extreme rainfall and antecedent soil moisture condition from year to year. This aleatory uncertainty influences the shape of the flood frequency distribution, and influences the values of 1% Annual Exceedance Probability design flood estimates. The aleatory uncertainty is why practitioners undertake a risk-based design approach to estimate the likelihood of flooding. At different catchments, the flood frequency distribution changes due to the natural variability in the climate and catchment processes, hence this is also of type aleatory uncertainty.

An illustration of epistemic uncertainty is the uncertainty in the estimate of the design flood for a given Annual Exceedance Probability, e.g. Figure 1.2.2, the design flood for a 1% Annual Exceedance Probability has an expected flow of 100 m^3/s and the 95% probability limits are 65 and 155 m^3/s. This uncertainty in the design flood estimate for a given Annual Exceedance Probability is primarily of type epistemic (or knowledge based) uncertainty. There is an opportunity to reduce this uncertainty, if there were longer flow records which would reduce the uncertainty in the parameters of the flood frequency distribution fitted to the annual maximum floods. Similarly, for catchment modelling, or if there was a better understanding on the catchment processes obtained through better data to calibrate and verify the catchment modelling system, this would reduce the uncertainty in the flood estimates of the catchment model.

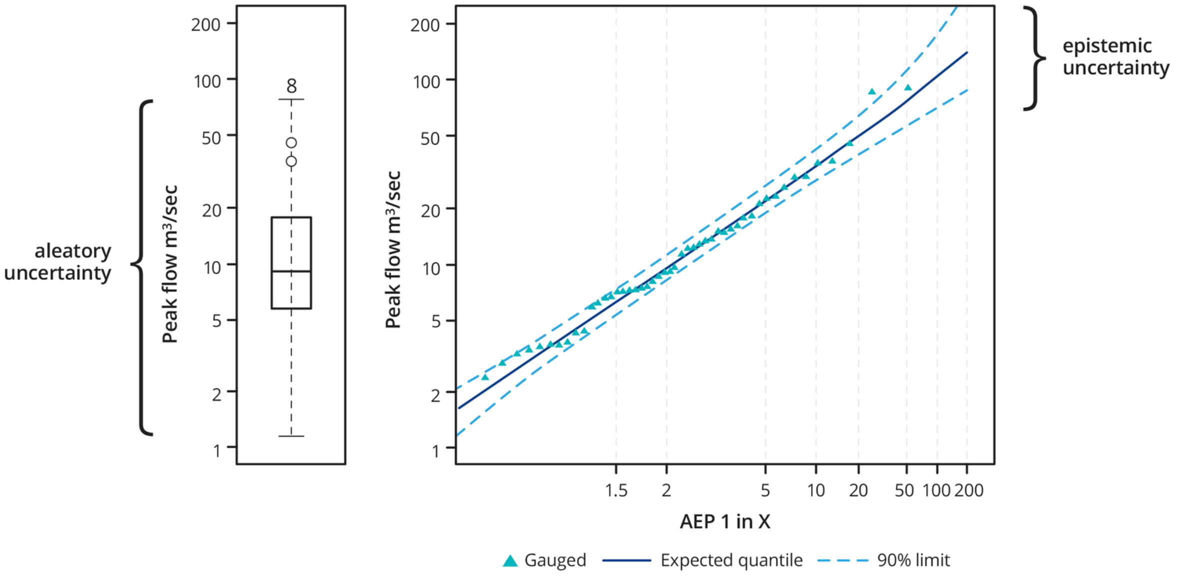


Figure 1.2.2. Different Types of Uncertainty, Aleatory and Epistemic, in the Context of Design Flood Estimation

Despite the simplicity of the two illustrations of aleatory and epistemic uncertainty, given in the flood frequency distribution in Figure 1.2.2, there are occasions where the distinction between the two different types of uncertainty is not always clear. For example, the illustration of Figure 1.2.2 implies that as level of information increases and the epistemic uncertainty is reduced then "true" flood frequency distribution for a given catchment will emerge. There is practical limit on the level of information (data and/or process understanding) available on a given catchment hence the concept of a single "true" flood frequency distribution for a given catchment is likely to unobtainable. Hence the epistemic uncertainty given in Figure 1.2.2, will have a component of aleatory uncertainty.

The concepts of aleatory and epistemic uncertainty are similar to concepts of flood likelihood and uncertainty from risk-based decision-making (Book 1, Chapter 5).

2.8.3. Motivation for Incorporating Uncertainty Into Design Flood Estimates

There are a range of approaches for dealing with uncertainty, the simplest of which is to ignore it, to qualitative descriptions (highly uncertain) or relative rankings, (option 1 is more uncertainty than option 2) ie. to rigourous quantitative approaches which use uncertainty analysis techniques to characterise the individual sources of uncertainty, and use advanced techniques to estimate their impacts on the uncertainty in the design flood estimations (refer to Book 4, Chapter 3 for an overview of the various approaches). The greater the rigour in uncertainty analysis approach the more effort and resources is required. The reward for this greater effort is more informed decision making.

An example of the potential benefits of incorporating uncertainty for more informed decision making is provided in Figure 1.2.3. Consider two different designs; Design A and Design B. The practitioner needs to choose the design that reduces the flood magnitude for given catchment location. Design A has a higher value for the most likely estimate of the design flood, but has a lower uncertainty than Design B. The differences in the uncertainty estimates could arise because Design B is a more complicated design option than design A and requires the use of more complex catchment modelling approach (e.g. fully distributed model (Book 5)) and there was a lack of spatial data in the catchment to calibrate the distributed model and hence parameter estimates had to be based on regional information. In contrast Design A was based on catchment modelling approach that was well-calibrated using high quality data that was readily available in the catchment. If the uncertainty is ignored then Design B would be the preferred choice of the practitioner, because the most likely estimate of the flood magnitude is lower than Design A. If the uncertainty in the flood magnitude incorporated than a practitioner who is risk-averse may prefer to choose Design A, because it the probability of a large magnitude flood with major/catastrophic consequence is lower than Design B. This example illustrates how the uncertainty in the design flood estimates, when combined with risk attitude (risk-averse, risk-neutral, or risk-seeking) of the practitioner provides a more information on which to base the design choice.

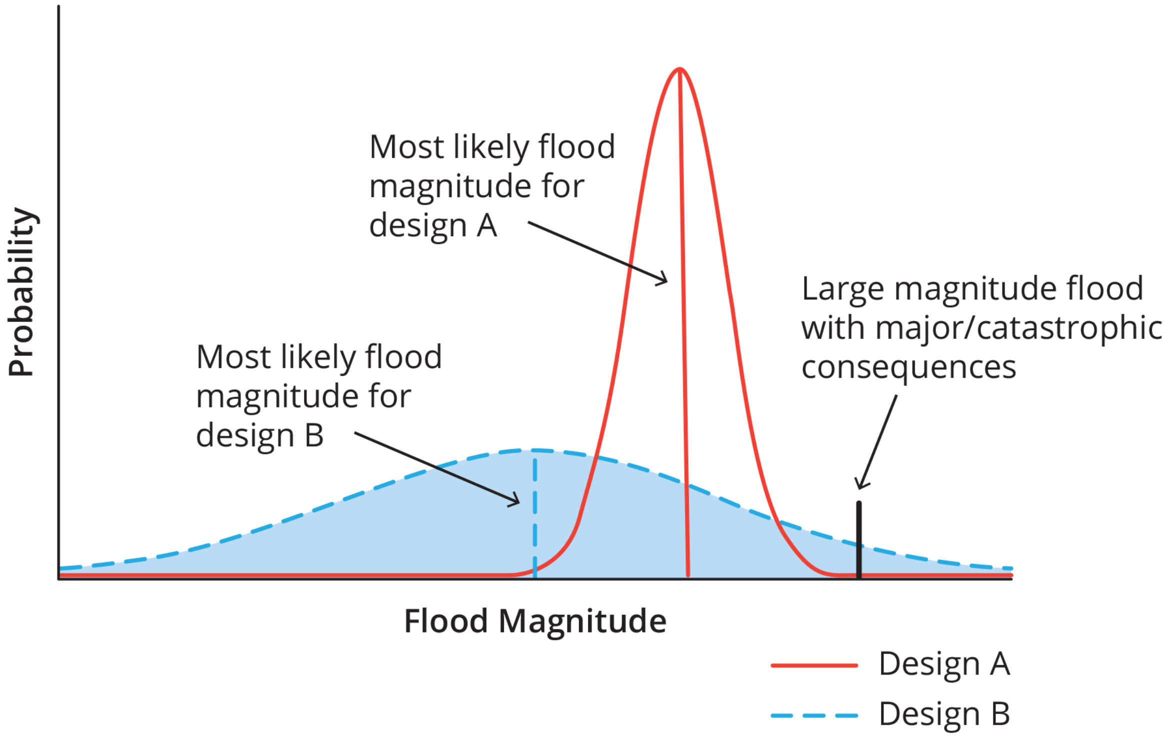


Figure 1.2.3. Impact of Uncertainty on a Design Flood Estimate for Two Design Cases

From a practical and scientific perspective Pappenberger and Beven (2006) provide an overview of the common reasons for not undertaking uncertainty analysis for hydrologic and hydraulic models and argue that these arguments are not tenable. A summary of the reasons provided by Pappenberger and Beven (2006) and their counter arguments are summarized as follows:

1. *Uncertainty Analysis is Not Necessary Given Physically Realistic Models*

   Pappenberger and Beven (2006) states there are a group of practitioners who believe that their models are (or at least will be in the future) physically correct and thus parameter calibration or uncertainty analysis should not be necessary (or only minimal) if predictions are based on a true understanding of the physics of the system simulated. This position is difficult to justify considering published discussions of the modelling process in respect of the sources and impacts of uncertainties (Beven, 1989; Beven, 2006; Oreskes et al., 1994). It is argued that this group of practitioners have too much faith in the model representation of physical laws or empirical equations. An alternative is a group of practitioners who inherently accept uncertainties in the modelling process, at least as a result of errors and natural variability in time and space.

2. *Uncertainty Analysis is Not Useful in Understanding Hydrological and Hydraulic Processes*

   To be able to learn about how water flows through the landscape and the best model to represent this water flow requires the use of a hypothesis testing framework . In real applications, this hypothesis testing framework would evaluate different competing hypothesis (ie. models) against the observations, and should explicitly consider the potential sources of uncertainty in applications to real systems to enable the results to be stated in a probabilistic rather than a deterministic manner. This would enable evaluation of whether the differences in model performance, can be reliability identified given the uncertainty in the predictions and observations.

3. *Uncertainty (Probability) Distributions Cannot be Understood by Policy Makers and the Public*

   Pappenberger and Beven (2006) cite several scientific studies that suggest practitioners actually want to get a feeling for the range of uncertainty and the risk of possible outcomes. Furthermore, policy-makers derive decisions on a regular basis under severe uncertainties. If uncertainty is not communicated and there is a misunderstanding of the certainty of modeling results this can lead to a loss of credibility and trust in the model and the modelling process.

   However, it is acknowledge that there are a wide range of different perceptions of “risk” and “uncertainty” and that effort is required on the part of both pracitioners and policy-makers to work together to achieve a common understanding of uncertainty.

4. *Uncertainty Analysis Cannot be Incorporated into the Decision-Making Process*

   There are two supporting arguments to this reason (1) Decisions are binary; (2) Uncertainty bounds are too wide to be useful in decision making. Pappenberger and Beven (2006) conclude there is no question that, for many environmental systems, a rigorous estimate of uncertainty leads to wide ranges of predictions. There are certainly cases in which the predictive uncertainty for outcomes of different scenarios is significantly larger than the differences between the expected values of those scenarios. This leads to the perception that decisions are difficult to make. To counter these arguments, Pappenberger and Beven (2006) present numerous examples from the literature on decision support systems and decision analysis which provide a range of methods for decision making under uncertainty based on assessments of the risk and costs of possible outcomes. Examples of decisions under uncertainty for Flood Frequency Analysis are illustrated by Wood and Rodriuez-Iturbe (1975) and more recently by Botto et al. (2014). The key outcome from Botto et al. (2014) was that incorporating uncertainty in estimating the design floods (by minimising the total expected costs) leads to substantial higher estimates of the design flood compared to standard approaches when uncertainty is ignored. This suggests incorporating uncertainty leads to reduce expected costs and highlights the benefits of incorporating uncertainty.

5. *Uncertainty Analysis is Too Subjective*

   Pappenberger and Beven (2006) identify that in the application of uncertainty analysis methods, certain decisions must be made, some of which include an element of subjectivity, including the choice of probability distributions for data errors, prior distributions for parameter uncertainty or predictive errors. In principle, many of these assumptions can be checked as part of the analysis but it is common to find that not all assumptions can be fully justified or some assumptions cannot be checked, and hence this leads to the conclusion that predictions with uncertainty are too subjective. Pappenberger and Beven (2006) conclude that any analysis which does not considering uncertainties in the modeling can be objective. This view is based on a misplaced faith in deterministic modeling in the light of the inevitable uncertainty in the modeling process (refer to also argument 1 above). Even a fully deterministic model run requires necessarily subjective assumptions about model inputs and boundary conditions and performance evaluation. The important issue is that the nature of the assumptions should be made explicit so that they can be assessed and discussed. Uncertainty analysis provides a set of tools to make these assumptions transparent and subject them to explicit scrutiny.

6. *Uncertainty Analysis is Too Difficult to Perform*

   Pappenberger and Beven (2006) note this is a common attitude amongst practitioners and is consequence of the need to spend more time and money on assessing the different potential sources of uncertainty in any particular application, coupled with a lack of clear guidance about which methods might be useful in different circumstances. Pappenberger and Beven (2006) note that in general, uncertainty analysis is not too difficult to perform and provide list of relevant software that is available. Since, Pappenberger and Beven (2006) review, the research publications on uncertainty analysis in hydrologic modelling has increased substantially, with many new tools/techniques and reviews available (for example the recent review by Uusitalo et al. (2015)). These tools will be reviewed to provide guidance for practitioners on which is applicable for different situations in the context of design flood estimation. The continued increases in computational power have reduced the computational costs of uncertainty analysis, which reduces the difficulty in undertaking uncertainty analysis.

In summary, Pappenberger and Beven (2006) conclude that in the past many modelling and decision making processes have ignored uncertainty analysis and it could be argued that under many circumstances it simply would not have mattered to the eventual outcome. However, they note that the arguments for uncertainty analysis are compelling because:

1. It makes the practitioner think about the processes involved and the decisions made based on model results;

2. It makes predictions of different experts more comparable and leads to a transparent science;

3. It allows a more fundamental retrospective analysis and allows new or revised decisions to be based on the full understanding of the problem and not only a partial snapshot; and

4. Decision makers and the public have the right to know all limitations in order to make up their own minds and lobby for their individual causes.

2.8.4. Sources of Uncertainty in Context of Design Flood Estimation

Book 1, Chapter 2, Section 8 outlined the practical advantages of undertaking uncertainty analysis. The first step of undertaking uncertainty analysis is to identify the various sources of uncertainty in the modelling processes. To raise awareness of the various sources of uncertainty in the context of design flood estimation, this section will outline the various sources of uncertainty and identify how these sources of uncertainty manifest themselves in the two common techniques used for design flood estimation; the Flood Frequency Analysis and catchment modelling approaches to design flood estimation. The primary drivers of each of the sources of uncertainty will then also be discussed.

The various sources of uncertainty that are relevant to design flood estimation are outlined as follows:

- *Predictive Uncertainty*

Predictive uncertainty represents the total uncertainty in the predictions of interest, typically the estimates of the design flood. It is comprised of the various sources of uncertainty that are outlined below, including data uncertainty, parametric uncertainty, structural uncertainty, regionalisation uncertainty (if relevant) and deep uncertainty (if relevant). This total predictive uncertainty is what used as input to the decision making uncertainty framework, to provide reliable predictions. The magnitude of the total predictive uncertainty and the relative contribution of the various sources of uncertainty is of obvious interest. The magnitude provides an indication of the total uncertainty of the predictions, while the relative contribution highlights which sources of uncertainty are the key contributors and which can be reduced.

- *Data Uncertainty*

Data uncertainty is a key source of predictive uncertainty. The more uncertain the data used to inform the methods used to estimate the peak flows, the more uncertainty in the predictions of the peak flows. The definition of “data” is a challenging one in the context of design flood estimation since in each step of the modelling process, the data used an input maybe based on the output of a prior modelling process, rather than actual measurements. Data uncertainty is dependent on the quality and number of measurements undertaken to inform that data.

- *Parametric Uncertainty*

Design flood estimates relay on using mathematical models to predict design floods. These models are estimated using time series of uncertain data with finite length. These limitations induce uncertainty in the estimates of these parameters, called parametric uncertainty. This parametric uncertainty would occur even if the mathematical model were exact. The magnitude of this parametric uncertainty, decreases as the length of the time series of data increases and increases when the uncertainty of the data increases. When time series are short and/or uncertainty in the data are high then parametric uncertainty can contribute significantly to total predictive uncertainty.

- *Structural Uncertainty*

Structural uncertainty refers to the uncertainty in the mathematical model used to provide the predictions of the peak flows. It is a consequence of the simplifying assumptions made in approximating the actual environmental system with a mathematical hypothesis (Renard et al., 2010). The structural error of a hydrologic model depends the model formulation.

- *Regionalisation Uncertainty*

Regionalisation uncertainty refers to the uncertainty induced when there is a geographical migration of hydrological information from data rich location to a data poor location. This is an extension of the concepts of regionalisation of hydrologic model parameters, as outlined by Buytaert and Beven (2009). In the context of design flood estimation itt refers to any information that is transferred from one site to another, and could include the parameters of the flood frequency distribution, the parameters of the runoff-routing model, the loss model or the design rainfall used in the catchment modelling approach. It is a function of the predictive uncertainty of the original application of the model at the data rich location (which is a dependent on the structural, parametric and data uncertainty at that data rich site) and the regionalisation model used to transfer information from one site to another. Given there are large number of sources of uncertainty in regionalisation uncertainty, it can induce significant predictive uncertainty, when there is very limited at-site data.

- *Deep Uncertainty*

Deep uncertainty refers to the sources of uncertainty that impact on the robustness of design but are difficult to assign apriori probabilities measures to. It acknowledges that practitioners and decision makers may not be able to enumerate all sources of uncertainty in a system nor their associated probabilities (Herman et al., 2014). It is related to the emerging field of robust decision making, where it is assumed that future states of the world are deeply uncertainty and instead of assigning probabilities, it seeks to identify robust strategies which perform well across the range of plausible future states. In the context of design flood estimation, examples of deep uncertainty could include the effects of climate change, because the different scenarios used for future greenhouse gas emissions cannot be assigned probabilities, another example might be future land use changes within a catchment, because it depends on variety of political, social and economic factors, which can be difficult to reliably assign probabilities. This source of uncertainty requires a different approach to the other sources, where scenario analysis is used to test the system and identify thresholds where significant failures occur. This approach has seen recent application in analysing water resources systems for long-term drought planning, however the application in flood design is limited. Given this is still a burgeoning area with significant research required, the approaches to treat this source of uncertainty will not be further considered in the scope of this uncertainty in Australian Rainfall and Runoff.

2.8.5. Raising Awareness of the Sources of Uncertainty in Techniques Used for Design Flood Estimation

In this section, it will be illustrated how to identify the sources of uncertainty for the two common techniques used for design flood estimation; Flood Frequency Analysis and catchment modelling. The identification of the sources of uncertainty involves the following steps:

1. Identify the information required for each step of the methods; and

2. Identify the potential sources of uncertainty in the information required for each of the steps.

Uncertainty is related to the level of information (ie. available of at-site data, its length and quality). For the purposes of this illustration, two different scenarios of available information will be considered (a) Using at-site data (b) No at-site data available, using regional information only. In practise, the level of information will be commonly be somewhere in between these two scenario, nonetheless these two scenarios provide convenient “use” case, to illustrate the identification of the sources of uncertainty.

The relative contribution of each of these sources of uncertainty to the total predictive uncertainty is catchment specific, and depend on a range of factors (outlined below). Hence, to evaluate and determine the dominant source of uncertainty in a particular catchment requires a rigourous uncertainty analysis. Hence the following description will focus on describing the various source of uncertainty for each of the steps in both Flood Frequency Analysis and catchment modelling and identify the factors that will impact on the magnitude of that particular source. In any particular combination of information available means that one source could dominant the other. Hence in the following descriptions, each uncertainty source will not be described as low or high, rather the description will identify what increases or decreases the magnitude of the sources uncertainty.

2.8.5.1. Flood Frequency Analysis

1. *Estimate Flood Frequency Distribution Parameters*

   a. Using At-site Data

   Data Uncertainty

   When using at-site streamflow data to estimate the Flood Frequency Distribution, the data uncertainty in this streamflow data is a source of uncertainty. The factors that effect the magnitude of this source of uncertainty are primarily the quality of the rating curve used to estimate the streamflow, the number of gaugings (and their quality), the degree of extrapolation of the rating, the stability of the rating curve, among others (Le Coz et al., 2013).

   Parametric Uncertainty

   As parameters of the Flood Frequency Distribution are estimated based on limited time series of data, this induces uncertainty in the parameters. This parametric uncertainty is determined by the length of data (uncertainty increases as the length decreases) and the quality of the data (parametric uncertainty increases as data uncertainty increases).

   Structural Uncertainty

   The source of structural uncertainty is the assumed form of the food frequency distribution probability model, ie. log-Normal, Log Pearson III etc. When calibrating to at-site data, this source of uncertainty can be checked by comparing against the observed data, to determine if the quality of the fit to observed data.

   b. Using Regional Information without At-site Data

   Data, Parametric, and Structural Uncertainty

   When there is no at-site data, then regional information is used to inform the parameters and the choice of the probability model used for the flood frequency distribution. For this case, there data uncertainty is not a source of uncertainty, however the parametric uncertainty is higher than case (a), because no at-site data is available, and the structural uncertainty is also high than case (a) because no at-site data is available to evaluated if the chosen probability model for the flood frequency distribution is appropriate.

   Regionalisation Uncertainty

   When using regional information there is also regionalisation uncertainty because the parameters of the flood frequency has been transferred from another catchment. All the sources of uncertainty that contribute to the regionalisation uncertainty as described previously will be relevant to this source of uncertainty.

2. *Predicting Design Floods using Flood Frequency Analysis*

   In this Step 2 of predicting design floods using Flood Frequency Analysis, the data, parametric and structural uncertainty sources identified in Step 1 will be present. A additional contributor to the structural uncertainty when predicting design floods with Annual Exceedance Probability beyond the range of the streamdata (e.g. 1 in 100 Annual Exceedance Probability based on 30 years of streamflow data) is the assumption that the chosen probability model will provide a reliable estimate of design floods under extrapolation to the 1 in 100 or 1 in 200 Annual Exceedance Probability flood. This additional source of structural uncertainty will be present, irrespective of case (a) or case (b) levels of information. A longer time series of at-site streamflow data, and hence a lower degree of extrapolation will decrease, but not eliminate, the magnitude of this source of uncertainty.

2.8.5.2. Catchment Modelling Approach to Estimating Design Floods

The catchment modelling approach to design flood estimation relies on estimates of the design rainfall, which is converted into effective rainfall using a loss model and then used as input into runoff-routing model (calibrated to a limited number of flood events) to simulated flood events and therefore provide estimates of the design flood. The steps of this approach are at (1) Estimate runoff-routing model and loss model parameters (2) Estimating design rainfall and the temporal and spatial patterns (3) Predicting design floods using catchment modelling systems. These steps are outlined:

1. *Estimate Runoff-Routing Model and Loss Model Parameters*

   The parameters for the runoff-routing model and the loss model are usually calibrated jointly using flooding events in a given catchment. There are distinct components of the catchment modelling processes, however as their sources of uncertainty are similar, they will be discussed together.

   a. Using At-site Data

      Data Uncertainty

      Runoff-routing models (e.g. RORB) and loss models (e.g. required in the catchment modelling approach are typically calibrated to at-site flood event data. In this calibration step, the data uncertainty is the uncertainty in the streamflow data (discussed previously) and the additional uncertainty in the rainfall data, which as discussed previously, increases as the rainfall gauge density within the catchment decreases.

      Parametric Uncertainty

      The runoff-routing model loss model have parameters estimated through calibration to a limited number of flood events. This source of parametric uncertainty will decreases as the number of events decreases, and the consistency of the parameter estimates between events also increases. If the parameter estimates vary significantly between events, this will increase the parametric uncertainty.

      Structural Uncertainty

      As the runoff-routing model and the loss models represents a mathematical simplification of the actual catchment processes, will be a source of structural uncertainty. As the fit to the data used for calibration increases this source of uncertainty will decrease, but will not be eliminated. If the complexity of the runoff-routing model increases, e.g. move from lumped to a spatially distributed model, may potentially decreased the structural uncertainty, however, with a spatially distributed model the challenge becomes estimating the parameters over a spatial grid. Hence, if there is a lack of spatial streamflow and rainfall data to calibrate the model, than there is a potentially a shift from structural uncertainty to parametric uncertainty, which may results in no reduction the total predictive uncertainty.

b. Regional Information Only

Data, Parametric, and Structural Uncertainty

Similar to Flood Frequency Analysis, when there is no at-site data, the regional information is used to inform the parameter estimates, and choice of runoff-routing and loss model. For this case, there is data uncertainty is not a source of uncertainty, however the parametric uncertainty is higher than case (a), because no at-site data is available, and the structural uncertainty is also high than case (a) because no at-site data is available to evaluated if the runoff-routing model or loss model is appropriate.

Regionalisation Uncertainty

When using regional information there is also regionalisation uncertainty because the parameters of the runoff-routing model and loss model have been transferred from another catchment. All the sources of uncertainty that contribute to the regionalisation uncertainty as described previously will be relevant to this source of uncertainty, but they will apply both to the loss model and the runoff-routing model. In comparison to regionalisation of flood frequency distribution which is relatively well advanced , the regionalisation of runoff-routing models and loss models is still relatively unreliable and hence the regionalisation uncertainty of runoff-routing and loss models is likely to far larger than regionalisation of flood frequency distributions.

2. Estimating Design Rainfall and the Temporal and Spatial Patterns

In the majority of cases practitioners will use the design rainfall estimates provided by the Bureau of Meteorology, rather than undertake an Intensity Frequency Duration analysis of the observed rainfall data within a catchment, hence only the case when regional information is available will be considered in this description. There are many similarities to sources of uncertainty in the Flood Frequency Analysis, except the goal is to estimate extreme rainfall events rather than flow events.

Data, Parametric, Structural and Regionalisation Uncertainty

The source of data uncertainty is rainfall gauge density and the length of rainfall data across Australia, is highly variable in different parts of Australia and with far lower gauge density and shorter records for sub-daily rainfall data then daily. This can induce significant data uncertainty in the design rainfall estimates. Similar to Flood Frequency Analysis, a probability model is used to estimate the extreme rainfall events (e.g. 1 in 100 AEP) based on the limited rainfall data available. This probability model has parametric uncertainty, which increases as the length and quality of the rainfall data decreases. There is structural uncertainty in the choice of the probability model for extreme rainfall, and this is increased when the probability model is used to extrapolate to from shorter rainfall time series to extreme events. This is particular problematic for sub-daily rainfall, because records are typically shorter than daily rainfall data. There is regionalisation uncertainty because the design rainfall estimates are regionalised to areas with limited gauged data.

This design rainfall for an event is then disaggregated into a time series using temporal patterns, they have their own sources of data, parametric, structural and regionalisation uncertainty, because they are estimated based on rainfall data from outside the catchment of interest. If spatial patterns are used to distribute design rainfall spatially across a catchment, then they will similar sources of uncertainty.

Considering the high spatial and temporal variability of rainfall process these uncertainties in design rainfall are unlikely to be small.

3. Predicting Design Floods using Catchment Models

   When a catchment modelling approaches is used to predict design floods, the data, parametric, structural and regionalistion uncertainty identified in Steps 1 and 2 will be present. There are two sources of addition uncertainty, parameter uncertainty and structural uncertainty. These sources of uncertainty are because the runoff-routing and loss models in Step 1 are calibrated on runoff events are then extrapolated to larger design flow events, e.g. 1 in 100 AEP. The source of uncertainty is whether the parameters and model structural based on calibrations to (inevitable) smaller flood events can be applied to the larger design flow events.

2.8.5.3. Total Predictive Uncertainty

Table 1.2.1 provides a summary of the various sources of uncertainty for the two different techniques (Flood Frequency Analysis versus catchment modelling) for design flood estimation. It can be seen that due to the larger number of components in the catchment modelling, there are a greater number of sources of uncertainty in this process, compared with Flood Frequency Analysis. Typically when there are a larger number of sources of uncertainty the total predictive uncertainty is higher. Based on this analysis it can be concluded that catchment modelling is likely to have a higher total predictive uncertainty compared with Flood Frequency Analysis. However, the relative magnitude of the total predictive uncertainty for the two different techniques would vary on a catchment basis.

Table 1.2.1. Sources of Uncertainty in Design Flood Estimation

Steps	Information Available	Sources of Uncertainty			
		Data	Parametric	Regionalisation	Structural
Flood Frequency Analysis (FFA)					
1. Estimate Flood Frequency Distribution Parameters	a. At-site data	yes - streamflow	yes	No	yes
	b. Regional information only	No	yes – higher than case(a)	yes	yes – higher than case(a)
2. Predict Design Floods using Flood Frequency Analysis	Based on step 1	n/a - identified in step 1	n/a - identified in step 1	n/a - identified in step 1	yes - in addition to step 1

Steps	Information Available	Sources of Uncertainty			
		Data	Parametric	Regionalisation	Structural
Catchment Modelling					
1. Estimate Runoff-Routing Model and Loss Model Parameters	a. At-site data	yes – rainfall and streamflow	yes	No	yes
	b. Regional information only	No	yes – higher than case(a)	yes	yes – higher than case(a)
2. Estimate Design Rainfall and the Temporal/ Spatial Patterns	Based on Bureau of Meteorology IFD	yes – rainfall	yes	yes	yes
3. Predict Design Floods using Catchment Modelling Systems	Based on steps 1-2	n/a – identified in steps 1-2	yes – in addition to steps 1-2	n/a – identified in steps 1-2	yes – in addition to steps 1-2

2.8.6. Summary

This overview of the uncertainty in design flood frequency estimation has identified the two different types of uncertainty in the context of design flood estimation, aleatory uncertainty (due to natural variability) and epistemic uncertainty (due to knowledge uncertainty). It then outlined the motivation for undertaking uncertainty analysis, which is to provide more informed and transparent information on the uncertainty in the design flood estimates to enable practitioners and design makers to make better judgements on the appropriate design. The major sources of uncertainty in the context of design flood estimation were then outlined, and include data (uncertainty in measurements), parametric uncertainty of the models used, structural uncertainty in the models mathematical representation of the physical process, regionalisation uncertainty when information is moved from data rich to data poor catchments, and the total predictive uncertainty, which is composed of the elements of the individual sources of uncertainty. To raise awareness of the sources of uncertainty in the different techniques used for design flood estimation were identified. The conclusion, was that comparing Flood Frequency Analysis and catchment modelling, due to the larger number of components, the catchment modelling technique has a larger number of sources of uncertainty than Flood Frequency Analysis, and hence this will likely lead to a higher predictive uncertainty. However, the magnitude of the total predictive uncertainty is catchment specific, depending the availability of data and knowledge of the processes that driver design flood events.

2.9. References

Abbs, D. and Rafter, T. (2008), The Effect of Climate Change on Extreme: Rainfall Events in the Westernport Region, CSIRO.

Ang, A. and Tang, W. (2007), Probability Concepts in Engineering, 2nd edition ed. Wiley, United States of America.

Bates, B., and Westra, S. (2013), Climate Change Research Plan - Summary. Report for Institution of Engineers Australia, Australian Rainfall and Runoff Guideline: Project 1.

Bates, B., Evans, J., Green, J., Griesser, A., Jakob, D., Lau, R., Lehmann, E., Leonard, M., Phatak, A., Rafter, T., Seed, A., Westra, S. and Zheng, F. (2015), Development of Intensity-Frequency-Duration Information across Australia - Climate Change Research Plan Project. Report for Institution of Engineers Australia, Australian Rainfall and Runoff Guideline: Project 1. 61p.

Bates, B. C., Z. W. Kundzewicz, S. Wu, and J. P. Palutikof (2008), Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, Rep., 210 pp, IPCC Secretariat, Geneva.

Beven, K. (1989), Changing ideas in hydrology - The case of physically-based models, Jounral of Hydrology, 105(1-2), 157-172.

Beven,A manifesto for the equifinality thesis, Journal of Hydrolology, 320: 18-36.

Botto, A., Ganora, D., Laio, F. and Claps, P. (2014), Uncertainty compliant design flood estimation, Water Resour Res, 50(5), 4242-4253. 10.1002/2013WR014981

Buytaert, W. and Beven, K. (2009), Regionalization as a learning process, Water Resour Res, 45(11).

CSIRO (2012), Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), CSIRO, Australia, September 2012, 41 pp.

CSIRO and Australian Bureau of Meteorology (2007), Climate Change in Australia, CSIRO and Bureau of Meteorology Technical Report, p: 140. www.climatechangeinaustralia.gov.au

Church, J.A., White, N.J., Hunter, J.R. and McInnes, K.L. (2012), Sea level. In A Marine Climate Change Impacts and Adaptation Report Card for Australia 2012 (Eds. E.S. Poloczanska, A.J. Hobday and A.J. Richardson). Available at: http://www.oceanclimatechange.org.au ISBN: 978-0-643-10928-5.

Fowler, H.J. and Ekstrom, M. (2009), Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes, International Journal of Climatology, 29(3), 385-416.

Groisman, P.Y, Karl T.R., Easterling D.R., Knight R.W., Jamason P.F., Hennessy K.J., Suppiah R., Page C.M., Wibig J., Fortuniak K., Razuvaev V.N., Douglas A., Forland E. and Zhai, P.M. (1999), Changes in the probability of heavy precipitation: Important indicators of climatic change,Climatic Change, 42: 243-283.

Herman, J. D., Zeff, H.B., Reed, P. M. and Characklis, G. W. (2014), Beyond optimality: Multistakeholder robustness tradeoffs for regional water portfolio planning under deep uncertainty, Water Resour Res, 50(10), 7692-7713, 10.1002/2014WR015338

Hunter, J. (2007), Estimating sea-level extremes in a world of uncertain sea-level rise, 5th Flood Management Conference, Warrnambool, Australia, [Accessed 12 October. 2007].

IPCC (Intergovernmental Panel on Climate Change) (2007), Climate Change 2007, Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC (Intergovernmental Panel on Climate Change) (2012), Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Socio-Economic Scenarios [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, V. Barros, C.B. Field, T. Zwickel, S. Schloemer, K. Ebi, M. Mastrandrea, K. Mach, C. von Stechow (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam Germany, p: 51.

Jones, M.R., (2012), Characterising and modelling time-varying rainfall extremes and their climatic drivers. PhD Thesis, Newcastle University.

Langbein, W.B. (1949), Annual floods and the partial-duration flood series, Transactions, American Geophysical Union, 30(6), 879-881.

Le Coz, J., Renard, B., Bonnifait, L., Branger, F. and Le Boursicaud, R. (2013). Uncertainty Analysis of Stage-Discharge Relations using the BaRatin Bayesian Framework. 35th IAHR World Congress, 08/09/2013 - 13/09/2013, Chengdu, China.

Nicholls, N. and Alexander, L. (2007), Has the climate become more variable or extreme? Progress 1992?2006, Progress in Physical Geography, 31: 77-87.

Oreskes, N., Shrader-Frechette, K. and Belitz, K. (1994), Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences, Science New Series, 263: 641-646.

Pappenberger, F. and Beven, K. J. (2006), Ignorance is bliss: Or seven reasons not to use uncertainty analysis, Water Resour Res, 42(5), 8, W05302 10.1029/2005wr004820

Pilgrim, DH (ed) (1987) Australian Rainfall and Runoff - A Guide to Flood Estimation, Institution of Engineers, Australia, Barton, ACT, 1987.

Renard, B., Kavetski, D., Kuczera, G., Thyer, M. and Franks, S.W. (2010), Understanding predictive uncertainty in hydrologic modeling: The challenge of identifying input and structural errors, Water Resour. Res., 46(5), W05521, 10.1029/2009wr008328.

Trenberth KE (2011), Changes in precipitation with climate change. Clim Res 47: 123-138.

Uusitalo, L., Lehikoinen, A., Helle, I. and Myrberg, K. (2015), An overview of methods to evaluate uncertainty of deterministic models in decision support, Environmental Modelling & Software, 63: 24-31, http://dx.doi.org/10.1016/j.envsoft.2014.09.017.

Westra, S., L.V. Alexander, F.W. Zwiers (2013), Global increasing trends in annual maximum daily precipitation. Journal of Climate, in press, doi:10.1175/JCLI-D-12-00502.1.

White, C.J., Grose, M.R, Corney, S.P., Bennett, J.C., Holz, G.K., Sanabria, L.A., McInnes, K.L., Cechet, R.P., Gaynor, S.M. and Bindoff, N.L. (2010), Climate Futures for Tasmania: extreme events technical report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.

Wood, E.F. and Rodriguez-Iturbe, I. (1975), Bayesian inference and decision making for extreme hydrologic events, Water Resour Res, 11(4), 533-542, 10.1029/WR011i004p00533.

Chapter 3. Approaches to Flood Estimation

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Chapter Status	Final
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3.1. Introduction

Design flood estimation is a focus for many engineering hydrologists. In many situations, advice is required on flood magnitudes for the design of culverts and bridges for roads and railways, the design of urban drainage systems, the design of flood mitigation levees and other flood mitigation structures, design of dam spillways, and many other situations. The flood characteristic of most importance depends on the nature of the problem under consideration, but it is often necessary to estimate peak flow, peak level, flood volume, and flood rise. The analysis might be focused on a single location (such as a bridge waterway or levee protecting a township) or it may be necessary to consider the performance of the whole catchment as a system, as required in urban drainage design.

Design objectives are most commonly specified using risk-based criteria, and thus the focus of this guidance is on the use of methods that provide estimates of flood characteristics for a specified probability of exceedance (referred to as flood quantiles, see Book 1, Chapter 2, Section 2).

The general nature of the estimation problem is illustrated in Figure 1.3.1. This figure shows the annual maxima floods (blue circular symbols) from 75 years of available gauged records. These flood maxima have been ranked from largest to smallest and are plotted against an estimate of their sample exceedance probability (as described in Book 3). Such information can be used directly to identify the underlying probability model of flood behaviour at the site at which the data was collected. The flood peaks are usually considered to be independent random variables, and it is often assumed that each flood is a random realisation of a single probability model. The gauged flood peaks shown in Figure 1.3.1 do appear to be from a homogeneous sample (ie. a single probability model), but in many practical problems the relationship between rainfall and flood may change over time, and it may be necessary to either censor the data or identify appropriate exogenous factors to condition the fit of the adopted probability model.

The best estimate of the relationship between flood magnitude and Annual Exceedance Probability (AEP) (Book 1, Chapter 2, Section 2) obtained by fitting a probability model is shown by the solid red curve in Figure 1.3.1. The gauged data represent a finite sample of a given size, and thus any estimate of flood risk using a fitted probability model is subject to uncertainty, as illustrated by the increasingly divergent dashed red curves in Figure 1.3.1 (referred to as confidence limits). The computation of such confidence limits usually only reflects the limits of the available sample, or perhaps the increasing uncertainty involved in the extrapolation of the relationship between recorded stage and estimated flood peak. The computed confidence limits are also conditioned on the assumed underlying probability model. However, it needs to be recognised that these factors only represent the uncertainties most easily characterised; other factors, such as the influence of a non-stationary climate, changing land-use during the period of record, and the changing nature of flood response with event magnitude, confound attempts to identify the most appropriate probability model. Accordingly, the true uncertainty around such estimates will be larger than that based solely on consideration of the size of the available sample. Of course, data are rarely available at the location of design interest, and additional uncertainty is involved in the scaling and/or transposition of flood risk estimates to the required site.

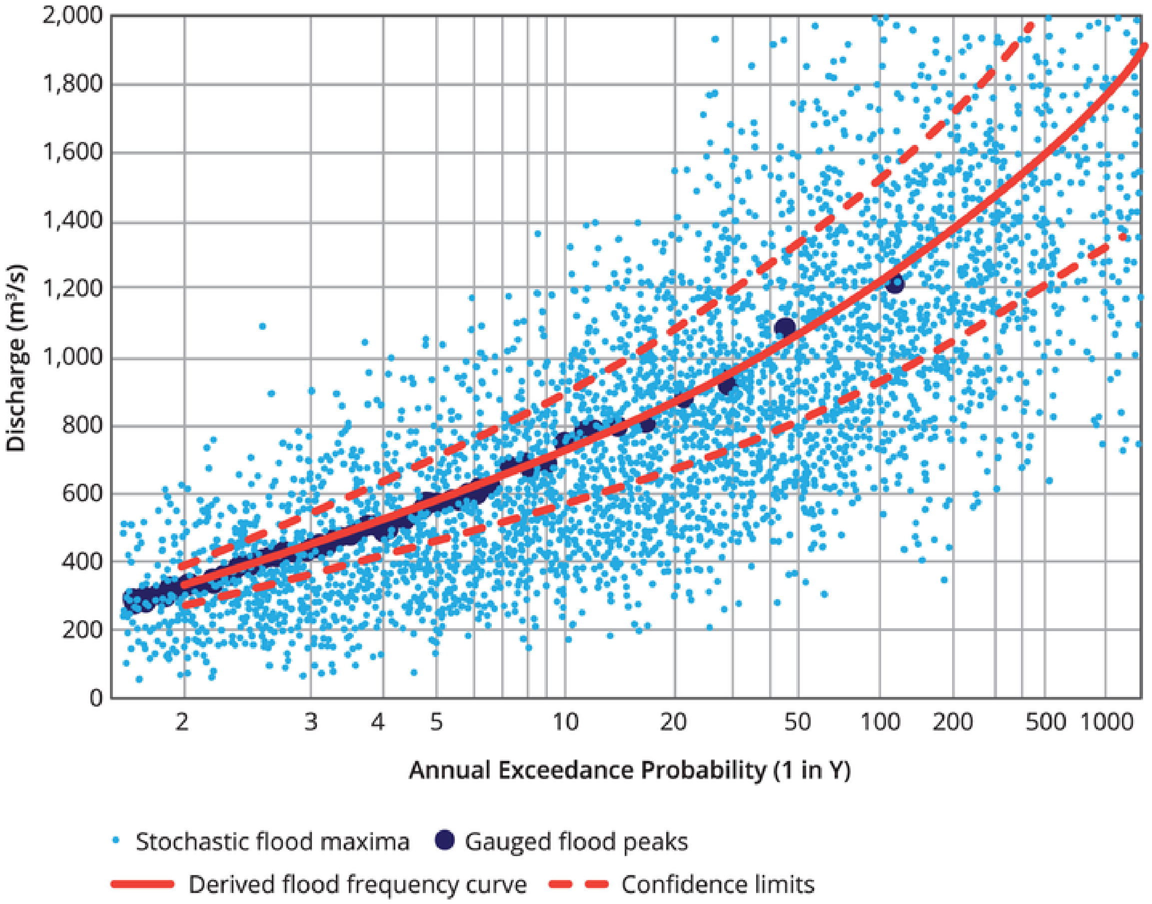

Figure 1.3.1. Illustration of Stochastic Influence of Hydrologic Factors on Flood Peaks and the Uncertainty in Flood Risk Estimates Associated with Observed Flood Data

One of the great advantages of fitting a probability flood model to observed data is that the approach avoids the problem of considering the complex joint probabilities involved in flood generation processes. Floods are the result of the interaction between many random variables associated with natural and anthropogenic factors; natural factors include interactions between the characteristics of the rainfall event, antecedent conditions, and other stochastic factors such as tide levels and debris flows; anthropogenic factors might include the influence of dam and weir operations, urbanisation, retarding basins, flood mitigation works, and land-management practices.

Figure 1.3.1 also illustrates the influence of natural variability on flood generation processes, and is based on the stochastic simulation of flood processes using 10 000 years of rainfall data under the assumption of a stationary climate. The stochastic flood maxima were obtained by varying key factors that influence the production of flood runoff, namely rainfall depth, initial and continuing losses, and the spatial and temporal patterns of catchment rainfalls. The flood peaks in Figure 1.3.1 are plotted against the AEP of the causative rainfall, and the scatter of the stochastic maxima illustrates the natural variability inherent in the production of flood runoff. While these maxima have been derived from mathematical modelling of event rainfall bursts, an indication of this variability can be seen in the relationship between observed rainfalls and runoff in gauged catchments (though of course with real-world data we do not have 10 000 years of observations).

The scatter of stochastic flood maxima resulting from different combination of flood producing factors illustrates the inherent difficulty in removing bias from “simple design event” methods. Such methods use a flood model to transform probabilistic bursts of rainfall (the design rainfalls as presented in Book 2) to corresponding estimates of floods. For example it is seen from Figure 1.3.1 that the flood peaks resulting from 1% AEP rainfalls range in magnitude between around 500 m^3/s and 2000 m^3/s; it is also seen that the rainfall that might generate a flood with a 1000 m^3/s peak might vary between a 20% and 0.1% AEP. Traditional practice has been to adopt fixed values of losses and rainfall patterns for use with design rainfalls to derive a single flood that is assumed to have the same AEP as its causative rainfall (probability neutrality). If chosen carefully it is possible to select a set of values that yields an unbiased estimate of the design flood for a particular catchment, but without taking steps to explicitly cater for the joint probabilities involved, there is a considerable margin for error (Kuczera et al., 2006; Weinmann et al., 2002).

Accordingly, a key difference between this and earlier versions of ARR is the focus on how best to achieve “probability neutrality” between rainfall inputs and flood outputs when using rainfall-based techniques. A number of more computationally intensive procedures are introduced (such as ensemble event, Monte Carlo event, and continuous simulation approaches) to help ensure that the method used to transform rainfalls into design floods is undertaken in a fashion that minimises bias in the resulting exceedance probabilities. An overview of these concepts is provided in Book 1, Chapter 3, Section 3, and more detailed description of the procedures is provided in Book 4.

The methods discussed here are divided into two broad classes of procedures based on:

i. the direct analysis of observed flood and related data (Book 1, Chapter 3, Section 2); and

ii. the use of simulation models to transform rainfall into flood maxima (Book 1, Chapter 3, Section 3).

All methods involve the use of some kind of statistical model (or transfer function) to extrapolate information in space or time. Each method also has its strengths and limitations and they vary in their suitability to different types of data and design contexts, and this is discussed in Book 1, Chapter 3, Section 4.

3.2. Flood Data Based Procedures

3.2.1. Overview

An overview of the procedures commonly used to analyse flood data directly is provided in Table 1.3.1. Flood frequency techniques (Book 1, Chapter 3, Section 2) are used to estimate the probability of flood exceedances directly from observed flood maxima, and are often used to extrapolate to probabilities beyond that inferred by the length of available record. Flood Frequency Analyses are most commonly applied using only the data at the site of interest using Peaks-over-Threshold and Annual Maxima Series (“at-site analyses”), but the resulting estimates of flood risk can be significantly improved by the consideration of flood behaviour at multiple sites that are judged to have similar flood frequency distributions (“at-site/regional analyses”). This concept of pooling information from multiple sites is often referred to as “trading space for time” for, with appropriate care, the information on flood exceedances across a region can improve the fit of the probability model at a single site with a short period of record.

One drawback of frequency analyses is that it can only provide quantile estimates at sites where data is available. Accordingly, a range of procedures have been developed to estimate flood risk at sites with little or no data (Book 1, Chapter 3, Section 2). These procedures generally involve the use of regression models to estimate the parameters of probability models (or the flood quantiles) using physical and meteorological characteristics, although simpler scaling functions can sometimes be used for local analyses.

Table 1.3.1. Summary of Common Procedures used to Directly Analyse Flood Data

	Frequency Analysis of Frequent Floods	**Frequency Analysis of Rare Floods**	**At-Site/Regional Flood Frequency Analysis**	**Regional Flood Frequency Estimation**
Inputs	Peak-over-Threshold series	Annual Maxima Series at single site of interest	Gauged flood maxima at multiple sites with similar flood behaviour	Catchment characteristics and flood quantiles (or parameters) derived from frequency analyses
Analysis	Selected probability model is fitted to flood maxima (e.g. exponential distribution fitted by L-moments)	Selected probability model is fitted to flood maxima (e.g. Log Pearson III/GEV distributions fitted by L-moments)	Information from multiple catchments is used to improve fit of probability model (e.g. regional L-moments or Bayesian inference)	Regression on model parameters or flood quantiles (e.g. RFFE method), or local scaling functions based on catchment characteristics
Outputs	Flood quantiles for AEPs > 10% at a gauged site	Flood quantiles for AEPs < 10% at a gauged site	Improved flood quantiles at multiple sites of interest	Flood quantiles at ungauged sites
ARR Guidance	Book 3, Chapter 2, Section 4 and Book 3, Chapter 2, Section 7	Book 3, Chapter 2, Section 4 and Book 3, Chapter 2, Section 6	Book 3, Chapter 2, Section 6 (Bayesian Calibration)	Book 3, Chapter 3

3.2.2. Flood Frequency Techniques

Flood Frequency Analysis involves the fitting of a probability model to recorded maxima to relate the magnitude of extreme events to their frequency of occurrence. The method can be applied directly to flood peaks (as described in Book 3) or rainfall (as used in Book 2), or indeed to any set of flood characteristics for which it is desired to determine the relationship between event magnitude and exceedance probability. The technique is generally not applicable to flood level maxima as the manner in which flood levels increase with flood magnitude is heavily dependent on channel geometry and thus is not suited to statistical extrapolation.

Flood Frequency Analyses can be broadly divided into three types of applications (Table 1.3.1), namely:

- At-site - the parameters of the probability distributions are fitted to annual maxima series to derive estimates of flood risk rarer than 10% AEP (or to peaks above a given threshold for more common floods) solely using information at the site of interest.

- At-site/regional - the information used to fit the model parameters is obtained from the site of interest as well as from other sites considered to exhibit similar flood behaviour.

- Regional - the information used to fit the model parameters is obtained from a group of sites considered to exhibit similar flood behaviour, where, as described in the following section, regression-based procedures may be used to estimate the model parameters (or probability quantiles) at the ungauged sites of interest.

Flood frequency methods are particularly attractive as they avoid the need to consider the complex processes and joint probabilities involved in the transformation of rainfall into flood. However, the utility of these methods is heavily dependent on both the length of available record and its representativeness to the catchment and climatic conditions of interest, as they are based on the assumption of stationary data series. Details on what distributions should be used, and how to select the sample of maxima and fit the distribution, are provided in Book 3.

There is advantage in undertaking frequency analyses at multiple sites in a local region of interest as this provides information on how local flood behaviour changes with catchment area, and other factors such as rainfall intensity can also be considered for more detailed analyses. Simple quantile regression models (ie. the development of a regression relationship between, say, catchment area and 10% AEP flood peak) are readily derived and are well suited to transposing flood risk estimates to locations upstream or downstream of a gauging site. Such simple scaling functions can also be applied to estimates derived using rainfall-based procedures.

3.2.3. Regional Flood Methods

Regional flood methods generally involve the application of a regression technique in which flood characteristics are related to catchment and relevant meteorological characteristics; the regression equation can be fitted to the flood quantiles directly (“quantile regression technique”), or else they can be fitted to the parameters of a probability model (“parameter regression technique”).

Book 3 provides details of the application of the latter approach to data sets for different Australian regions in which the three parameters of the probability model are estimated from catchment characteristics using a Bayesian regression approach (Rahman et al., 2014). The developed procedure provides a quick means to estimate the magnitude of peak flows between the 50% to 1% AEPs, with the additional attraction that uncertainty bounds are provided. The regression equations presented in Book 3 were developed using parameters obtained from at-site/regional flood frequency analyses, and thus represent a rigorous example of Regional Flood Frequency Estimation based on parameter regression.

In some situations it might be useful to obtain an additional independent estimate based on local data, and if so then prediction equations can be developed by regressing catchment characteristics against flood quantiles obtained from at-site/regional flood frequency analyses. The most common example of this is to develop a relationship between flood quantiles and catchment area for nested sites located in the same catchment (typically this is undertaken using log-transformed data). The utility of such an approach when compared to the procedure presented in Book 3 depends on the relevance of the data to the problem at hand, and on the extent to which the assumptions of the fitted model have been satisfied.

3.3. Rainfall-Based Procedures

3.3.1. General

Rainfall-based models are commonly used to extrapolate flood behaviour at a particular location using information from a short period of observed data; this can be done using either event-based or continuous simulation approaches, as described in Book 1, Chapter 3, Section 3 and Book 1, Chapter 3, Section 3 below. The parameters of such models can also be transposed to a different location (or modified to represent different catchment conditions) and used to estimate flood characteristics for which no gauging information is available.

Table 1.3.2 summarises the different characteristics of the event-based and continuous simulation approaches. The three broad approaches to event-based simulation all use the same hydrologic model to convert design rainfall inputs into hydrograph outputs, the main difference is in the level of sophistication used to minimise bias in the probability neutrality of the transformation. Continuous simulation approaches utilise model structures which generally differ markedly from those used in event-based models.

Event-based approaches are based on the transformation of rainfall depths of given duration and AEP (“design rainfalls”) into flood hydrographs by routing rainfall excess (obtained by applying a loss model to rainfall depths) through the catchment storage. Such models can include the allowance of additional pre- and post-burst rainfalls to represent complete storm events, and can separately consider baseflow contribution from prior rainfall events to represent total hydrographs. The defining feature of such models is that they are focused on the simulation of an individual flood event and that antecedent conditions need to be specified in some explicit fashion. Simple Design Event methods are applied in a deterministic fashion, where key inputs are fixed at values that minimise the bias in the transformation of rainfall into runoff. Alternatively, stochastic techniques can be used to explicitly resolve the joint probabilities of key hydrologic interactions; ensemble techniques provide simple (and approximate) means of minimising the bias associated with a single hydrologic variable, whereas Monte Carlo techniques represent a more rigorous solution that can be expanded to consider interactions from a range of natural and anthropogenic factors. It should be noted that the guidance provided in ARR only focuses on the use of stochastic techniques to cater for (random) variability of key inputs, and its use to characterise epistemic uncertainty is assumed to be the domain of specialist statistical hydrologists.

Continuous simulation approaches remove the need to specify antecedent conditions as these are implicitly considered in the successive updating of state variables via the simulation of continuous rainfall (and other) input time series. The continuous simulation of key state variables also has the potential to simplify the consideration of the complex joint probabilities involved in flood generation processes. The conceptual basis of continuous simulation is the simulation of data that would have been recorded at a location if a gauge were present at that location. Hence estimation of design flood characteristics from data generated through application of a continuous simulation modelling system requires the undertaking of subsequent statistical analysis, as outlined in Book 1, Chapter 3, Section 2. The advantages of continuous simulation may be offset by the need to consider additional complexity which are avoided by event-based approaches, though the relative merits of each approach is dependent upon the available data and the nature of the design problem being considered.

Table 1.3.2. Summary of Recommended Rainfall-Based Procedures

	Simple Design Event	**Ensemble Event**	**Monte Carlo Event**	**Continuous Simulation**
Hydrologic Inputs	Design rainfalls (ie. rainfall depth for given burst duration and Annual Exceedance Probability)			Observed (or synthetic) time series of rainfall and evaporation.
Hydrologic variability	Fixed patterns of rainfall and other inputs	Ensemble of *N* temporal patterns	Ensemble (or distribution) of temporal patterns, losses, and other factors.	As represented in the time series of inputs – if not in time series then not represented
Model	Event-based model based on routing rainfall excess through catchment storage (see Book 5 for details of technique)			Model of catchment processes influencing runoff generation
Framework	Single simulation for each combination of rainfall depth and AEP	*N* simulations for each combination of rainfall depth and AEP (N >10)	Stochastic sampling of input distributions using continuous or stratified domain (potentially thousands of simulations)	Continuous simulation at time step for *N* years
Flood AEP	Assumed same as input rainfall		Statistical analysis of joint probabilities (e.g. frequency analysis of maxima or Total Probability Theorem)	Computed from frequency analysis of *N* annual maxima
Flood magnitude	Single estimate derived from each set of inputs	Simple average (or median) of *N* simulations		
ARR guidance	Book 4	Book 4	Book 4	Book 4

3.3.2. Event-Based Simulation

The simple design event method represents common industry practice in Australia and overseas, and traditionally includes the use of the Rational Method, Unit Hydrograph, SCS, Gradex and runoff-routing procedures (Haan and Schulze, 1987; Cordery and Pilgrim, 2000; McKerchar and Macky, 2001; Smithers, 2012). With this approach, a rainfall event with pre-selected AEP and duration is transformed into a flood hydrograph by a simple hydrologic model (or transfer function). The approach is termed “deterministic” in the sense that the single resulting flood output is uniquely derived from a set of inputs that are explicitly selected. The transformation often involves the application of two modelling steps, namely:

i. a *runoff production model* - to convert the storm rainfall input at any point in the catchment into rainfall excess (or runoff) at that location, and;

ii. a *hydrograph formation model* - to simulate the conversion of rainfall excess into a flood hydrograph at the point of interest.

The AEP of the derived flood is assumed to be the same as the input rainfall. This assumption is made on the basis that the hydrologic factors that control runoff production are set to be probability neutral. In practice this means that factors related to the temporal and spatial distribution of rainfall, antecedent conditions and losses, are set to “typical” values (from the central tendency of their distributions) that are associated with the input rainfall. Factors related to formation of the hydrograph are generally assumed to be invariant with rainfall. Design events for different rainfall durations are simulated, and the one producing the highest peak flow (corresponding to the critical rainfall duration) is adopted as producing the design flood for the selected AEP (flood quantile).

The ensemble event method represents a modest increase in computational requirements. Rather than adopting typical fixed values of inputs in the hope of achieving probability neutrality, modelled inputs are selected from an ensemble of inputs and the simulation results are based on the central tendency of the outputs (ie. the average or the median, as judged appropriate for the degree of non-linearity involved). If the members of the ensemble do not occur with equal likelihood (as would usually be the case with temporal patterns) then it will be necessary to weight the results by the relative likelihood of the selected inputs occurring. A representative hydrograph from the ensemble can be scaled to match the derived peak for design purposes. This approach represents a simple means of accounting for the hydrologic variability of a single dominant factor (ie. temporal patterns), and testing has demonstrated (Sih et al., 2008; Ling et al., 2015; WMAwater, 2015) that this approach provides results for many practical purposes that are similar to that obtained from more rigorous methods.

The basis of the Monte Carlo event method is a recognition that flood maxima can result from a variety of combinations of flood producing factors, rather than from a single combination as is assumed with the design event approach. For example, the same peak flood could result from a large, front-loaded storm on a dry basin, or a moderate, more uniformly distributed storm on a saturated basin. Such approaches attempt to mimic the joint variability of the hydrologic factors of most importance, thereby providing a more realistic representation of the flood generation processes. The method is easily adapted to focus on only those aspects that are most relevant to the problem. To this end, it is possible to adopt single fixed values for factors that have only a small influence on runoff production, and full distributions (or data ensembles) for other more important inputs, such as losses, and temporal patterns, or any influential factor (such as initial reservoir level) that may impact on the outcome. The approach involves undertaking numerous simulations where the stochastic factors are sampled in accordance with the variation observed in nature and any dependencies between the different factors. In the most general Monte Carlo simulation approach for design flood estimation, rainfall events of different durations are sampled stochastically from their distribution (Weinmann et al., 2002). Alternatively, the simulations can be undertaken for specific storm durations (applying the critical rainfall duration concept) and the exceedance probability of the desired flood characteristic may be computed using the Total Probability Theorem (Nathan et al., 2002). The latter approach is simpler and more aligned to available design information, and is more easily implemented by those familiar with the traditional design event approach.

The simple design event approach gives a single set of design hydrographs that can be used for subsequent modelling steps, such as input to a hydraulic model to determine flood levels for a given exceedance probability. With the Ensemble and Monte Carlo event methods an ensemble of hydrographs is produced and it is often not practical to consider all these hydrographs in subsequent simulation steps. With both the ensemble and Monte Carlo approaches a representative hydrograph can be simply scaled to match the probability neutral estimate of the peak flood; the representative hydrograph needs to capture the typical volume and timing characteristics for the selected duration and severity of the event, though some of the advantages of ensemble and Monte Carlo event methods are lost if an ensemble of events is not used through all the key modelling steps.

3.3.3. Continuous Simulation

With continuous simulation approaches, a conceptual model of the catchment is used to convert input time series of rainfall and evaporation into an output time series of streamflow; the flood events of interest are then extracted from the simulated streamflow record and analysed by conventional frequency analysis. The models used to transform the input rainfall into streamflow tend to be rather more complex than those commonly used in the design event or stochastic approaches. The main reason for this complexity is the ability of the models to account for changes in state variables (e.g. soil moisture and other catchment stores) during the simulation period. While these models have been used for the past 40 years for the prediction of continuous flow sequences, their dominant purpose has been for estimation of flow sequences for either yield analysis or for environmental considerations (Chiew, 2010). However, their use has been extended to the estimation of design floods (Cameron et al., 2000; Boughton and Droop, 2003; Blazkova and Beven, 2004; Blazkova and Beven, 2009).

“Hybrid” approaches have the potential to capitalise on the advantage of both event-based and continuous simulation approaches. Typically, hybrid approaches use statistical information on rainfall events in combination with continuous simulation and event-based models. With these approaches, long term recorded (or stochastic) climate sequences can be used in combination with a continuous simulation model to generate a time series of catchment soil moisture and streamflows. This information is used to specify antecedent conditions for an event-based model, which is then used in combination with statistical information on rainfall events to generate extreme flood hydrographs. For example, SEFM (MGS Engineering Consultants, 2009) and SCHADEX (Paquet et al., 2013) are examples of the hybrid approach. In both these models a continuous hydrological simulation model is used to generate the possible hydrological states of the catchment, and floods are simulated on an event basis. While there are a number of conceptual advantages to these methods, significant development would be required for their implementation for routine design purposes.

3.4. Selection of Approach

3.4.1. Overview

The methods described above have their differing strengths and weaknesses, and this means that each method is suited to a particular range of data availability and design contexts. While the broad differences in the applicability of the different methods are discussed below, it should be recognised that there is considerable overlap in their ranges of applicability and it is strongly advisable to apply more than one method to any given design situation. The comparison of different methods yields insights about errors or assumptions that might otherwise be missed, and the process of reconciling the different assessments provides valuable information that aids adoption of a final “best estimate”.

In developing guidance on the selection of an approach it is first worth briefly summarising the strengths and weakness of the different methods. This is done separately for flood data based procedures and rainfall-based procedures, and this is then followed by general guidance for selection of an approach.

3.4.2. Advantages and Limitations of Flood Data Based Procedures

The prime advantage of Flood Frequency Analyses is that they provide a direct estimate of flood exceedance probabilities based on gauged data. Peak flood records represent the integrated response of a catchment to storm events and thus are not subject to the potential for bias that can affect rainfall-based procedures. Furthermore, Flood Frequency Analyses are quick to apply compared to rainfall-based procedures and have the ability to provide estimates of uncertainty, most easily those associated with the size of sample and gauging errors. These represent very considerable advantages, and thus it is not surprising that flood frequency analysis is an important tool for the practicing flood hydrologist.

However, there are some practical disadvantages with the technique. The available peak flood records may not be representative of the conditions relevant to the problem of interest: changing land-use, urbanisation, upstream regulation, and non-stationary climate are all factors that may confound efforts to characterise flood risk. The length of available record may also limit the utility of the flood estimates for the rarer quantiles of interest. Also, peak flow records are obtained from the conversion of stage data and there may be considerable uncertainty about the reliability of the rating curve when extrapolated to the largest recorded events. There is also uncertainty associated with the choice of probability model which is not reflected in the width of derived confidence limits: the true probability distribution is unknown and it may be that different models may fit the observed data equally well, yet diverge markedly when used to estimate flood quantiles beyond the period of record.

Perhaps the most obvious limitation of Flood Frequency Analysis is that it relies upon the availability of recorded flood data. This is a particular limitation in urban drainage design as there are so few gauged records of any utility in developed catchments. But the availability of representative records is also often a limitation in rural catchments, either because of changed upstream conditions or because the site of interest may be remote from the closest gauging station.

For this reason, considerable effort has been expended on the development of a regional flood model that can be used to estimate flood quantiles in ungauged catchments (Book 3, Chapter 3). The prime advantage of this technique is that it provides estimates of flood risk (with uncertainty) using readily available information at ungauged sites; the estimates can also be combined with at-site analyses to help improve the accuracy of the estimated flood exceedance probabilities. The prime disadvantage of the technique is that the estimates are only applicable to the range of catchment characteristics used in development of the model, and this largely excludes urbanised catchments and those influenced by upstream impoundments (or other source of major modification).

The main advantages and limitations of flood data based procedures are summarised in Table 1.3.3. In addition to the points made above, specific mention is made of the applicability of Peak-over-Threshold analysis to events more frequent than 10% AEP, and the use of Annual Maxima Series for the estimation of rarer events. Also included in this table is reference to the use of large scale empirical techniques. While these techniques have the advantage of providing an indication of the upper limiting bounds on the magnitude of floods using national and global data sets (Nathan et al., 1994; Herschy, 2003), it is difficult to assign exceedance probabilities to such events and thus such procedures are better seen as a complement, and not an alternative, to traditional regional flood frequency techniques (Castellarin, 2007).

Table 1.3.3. Summary of Advantages and Limitations of Common Procedures used to Directly Analyse Flood Data

Method	Advantages	Limitations	Comments on Applicability
Peak-over-Threshold analysis	• Exceedance threshold can be selected to suit frequency range of most interest	• Sensitive to adopted independence criteria • Fewer generic software packages available to aid analysis	• Particularly suited to exceedance probabilities more frequent than 10% AEP • Requires development of transposition/ scaling functions for application to ungauged sites
At-site Flood Frequency Analysis based on Annual Maxima Series	• Well established procedures that are strongly supported by literature • Software readily available that includes assessment of uncertainty • Estimates obtained for modest investment of effort	• Rare estimates sensitive to length of available record, a small number of rare events, and assumptions of stationarity • Extrapolation best undertaken with knowledge of changing channel geometry and rating curve errors	• Requires development of transposition/ scaling functions for application to ungauged sites
At-site/ regional frequency analysis based on Annual Maxima Series	• Well established procedures that are strongly supported by literature • Provides more robust estimates of rare events, especially for sites with limited length of record	• Dependent on degree of homogeneity of gauged sites used in the analysis • Requires more specialist expertise than at-site analysis	• Functions for transposition to ungauged sites readily derived from regional information used to undertake the analysis
Regional flood model	• Based on rigorous statistical procedure that takes advantage of large processed data sets • Estimates include uncertainty and are derived with small investment of effort	• Largely restricted to catchments smaller than 1000 km² • Flood response needs to be within range of characteristics used in development of the method • larger degree of uncertainty (wider confidence limits)	• Ease of application allows this to be used as independent estimate for all other methods

Method	Advantages	Limitations	Comments on Applicability
		than flood estimates from at-site analysis • Representativeness of the gauges used	
Large scale empirical	• Estimates readily obtained once relevant data sets have been sourced • Generally a useful indicator of the upper bound of flood behaviour	• Enveloped characteristics may not be relevant to site of interest • Not suited to inferring probabilities of exceedance	• Useful as a sanity check on results obtained from other procedures • Regional nature of information allows for application to ungauged sites

3.4.3. Advantages and Limitations of Rainfall-Based Procedures

A key advantage of rainfall-based approaches is that they provide the means to derive flood hydrographs. The derivation of a full hydrograph rather than a single attribute (such as flood peak) allows the design loading condition to be assessed in terms of both peak and volume, which is of prime importance when considering the mitigating influence of flood storage.

Of arguably greater importance is the ability of rainfall-based approaches to take advantage of the extensive availability of rainfall data. This is a very important advantage as rainfall characteristics vary across space in a more predictable and generally more uniform fashion than floods. This feature, along with the greater length and density of rainfall gauging, allows the derivation of probabilistic estimates of rainfalls that are much rarer and more easily transposed than flood characteristics.

However, these significant advantages are offset by the need to transform rainfalls into floods using some kind of design event transfer function or simulation model. Common examples of the former include the Rational Method and Curve Number method of the US Soil Conservation Service; while such methods provide an attractive means of simplifying the complexity involved in generation of flood peaks, their use in this edition has been replaced by the more defensible implementation of the Regional Flood Model (Book 3, Chapter 3). The focus of this guidance is thus on the use of event-based and continuous simulation approaches. While these models provide a conceptually more attractive means to derive flood hydrographs arising from storm rainfall events, they present the very real potential for introducing probability (AEP) bias in the transformation. That is, the methods are well suited to the simulation of flood hydrographs, but great care is required when assigning exceedance probabilities to the resulting flood characteristic.

The advantages and limitations of some common approaches to rainfall-based procedures are summarised in Table 1.3.4. The first row of this table summarises the attributes of continuous simulation approaches, and the remaining rows refer to event-based approaches.

The continuous simulation approach has the major advantage that it implicitly allows for the correlations between the flood producing factors over different time scales. This can be a great advantage in some systems (such as a cascade of storages or complex urban environments) where the volume of flood runoff is the key determinant of flood risk. However, its major drawback for flood estimation is that considerable modelling effort is required to reproduce the flood characteristics of interest; the structure of continuous simulation models is geared towards reproduction of the complete streamflow regime, and not on the reproduction of annual maxima. This has implications for model structure, as well as for how the model is parameterised and calibrated to suit the different flood conditions of interest. With continuous simulation, the vast majority of the information used to inform model parameterisation is not relevant to flood events other than to ensure that the right antecedent conditions prevail before onset of the storm. Under extreme conditions, many state variables inherent to the model structure might be bounded, and the process descriptions relevant to such states may be poorly formulated and yield outcomes that are not consistent with physical reasoning; while this is the case for flood event models, the more complex structure generally used with continuous simulation models may confound attempts to detect the occurrence of such behaviour. In addition, if the length of historic (sub-daily) rainfalls is not long enough to allow estimation of the exceedance probabilities of interest, it will be necessary to use stochastic rainfall generation techniques (or some down-scaling technique) to produce synthetic sequences of sufficient length. Lastly, given the interdependence between model parameters and the difficulty of parameter identification, it can be difficult to transpose such models to ungauged catchments.

The deterministic application of “design-event” models based on linear and non-linear routing has a long history of application in Australia. However, considerable care needs to be taken when selecting “typical” values of the key inputs to avoid the introduction of probability bias in the transformation of design rainfalls into floods. Ensemble event approaches have the potential to mitigate this bias, but these are only likely to be defensible for those problems influenced by a single dominant factor in addition to rainfall. Monte Carlo techniques can be used to derive expected probability quantiles of selected flood characteristics arising from the joint interaction of many factors, but the defensibility of these estimates rests upon the representativeness of the inputs and the correct treatment of correlations which may be present.

Table 1.3.4. Summary of Advantages and Limitations of Common Rainfall-Based Procedures

Method	Advantages	Limitations	Comments on Applicability
Continuous Simulation	• Well suited to assessing flood risk in complex systems that are sensitive to flood volume • Most applicable to range of very frequent to frequent events	• Difficult to parameterise model to correctly reproduce the frequency of flood exceedance in manner that adequately captures shape of observed hydrographs	• Useful for hindcasting streamflows for sites with short periods of record • Model parameters not easily transposed to ungauged locations
Simple Event	• Long tradition of use thus familiar to most practitioners	• Difficult to demonstrate that probability - neutrality is achieved	• Little justification to use this simplistic method with currently available computing resources, but suited to derivation of preliminary estimates

Method	Advantages	Limitations	Comments on Applicability
Ensemble Event	• Simple means of minimising probability bias for modest level of effort • Well suited to accommodating single source of hydrologic variability in simple catchments	• Not suited to considering multiple sources of hydrologic variability or other joint probability influences • Difficult to determine if probability bias remains in the estimates	• Provides easy transition for practitioners familiar with design event method • The required sets of ensemble temporal patterns are now available
Monte Carlo event	• Rigorous means of deriving expected probability estimates for range of factors considered • Readily extended to consider multiple sources of variability and additional joint probability factors (both anthropogenic and natural)	• Requires specialist skills to develop bespoke solutions and thus dependent on availability of software • For more complex applications care needs to be taken to ensure correlations between dependent factors are appropriately considered	• Non-dimensional loss distributions and temporal pattern ensembles are now available • The expected probability estimates account for hydrologic variability not parameter uncertainty as the necessary information on governing distributions is generally not available.

3.4.4. Relative Applicability of Different Approaches

The broad nature of applicability of the different methods is illustrated in Figure 1.3.2. Figure 1.3.2 is not intended to be prescriptive, but rather it is intended to illustrate the relative ability of the different methods to provide unbiased estimates of flood characteristics in the given AEP range. Figure 1.3.2 is best interpreted with reference to Table 1.3.3 which summarises the strengths and limitations of each method and provides some brief comments on their application.

Flood Frequency Analyses are most relevant to the estimation of peak flows for Very Frequent to Rare floods. Flood Frequency Analysis methods can also be applied to other flood characteristics (e.g. flood volume over given duration) but this involves additional assumptions.

Peak-Over-Threshold analysis (Book 3, Chapter 2, Section 7) is most relevant to the estimation of flood exceedances that occur several times a year, up to floods more frequent than around 10% AEP. For rarer events the use of an Annual Maximum Series is preferred (Book 3, Chapter 2, Section 6), and with good quality information at-site frequency analyses are suited to the estimation of Rare floods of 2% and 1% AEP. The use of regional flood data provides valuable information that can be used to help parameterise the shape of the flood distribution, and thus where feasible it is desirable to use at-site/regional flood frequency methods (Book 3, Chapter 2, Section 6). The use of regional information can support the estimation of flood risks beyond 1% AEP and can greatly increase the confidence of estimates obtained using information at a single site.

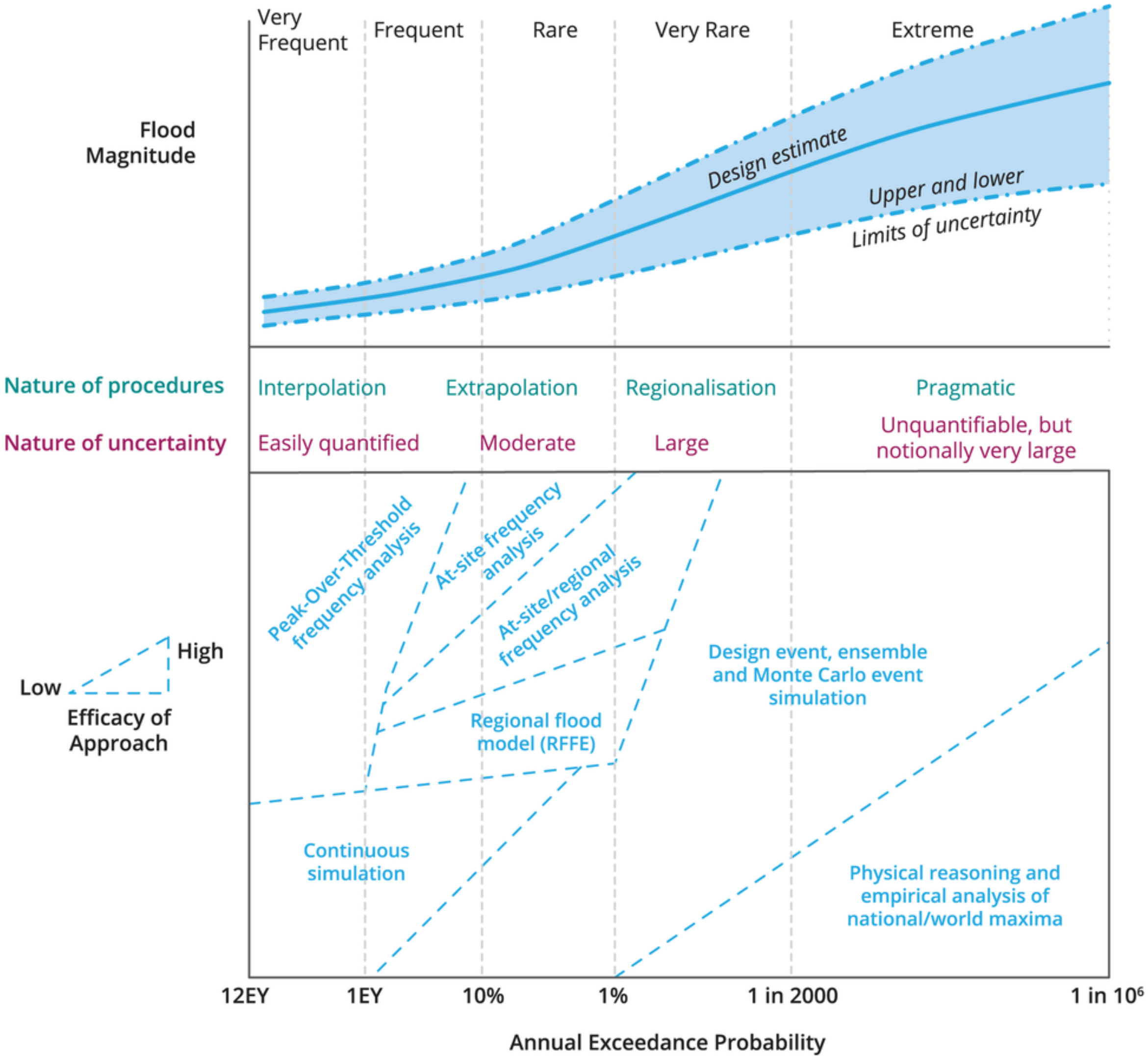

Figure 1.3.2. Illustration of Relative Efficacy of Different Approaches for the Estimation of Design Floods

The RFFE model (Book 3, Chapter 2, Section 6) (Rahman et al., 2014) provides estimates of peak flows for Frequent to Rare floods for sites where there is no streamflow data. While its primary purpose is for the estimation of flood quantiles, the resulting estimates can also be used to develop scaling functions to support the transposition of results obtained from rainfall-based procedures to ungauged sites. This is the same concept as the simple quantile regression approach discussed above, but as it is based on a more rigorous statistical procedure it is more suited to transposition of results where factors other than merely area are important. The RFFE method is quick to apply and provides a formal assessment of uncertainty, and thus is well suited to provide independent estimates for comparison with other approaches.

Figure 1.3.2 also illustrates the areas of design application most suited to rainfall-based procedures. These are applicable over a wider range of AEPs than techniques based directly on the analysis of flow data as it is easier to extrapolate rainfall behaviour across space and time than it is for flow data. But while these methods can capitalise on our ability to extrapolate rainfall data to rarer AEPs and infill spatial gaps in observations more readily than flows, their use introduces the need to model the transformation of rainfalls into floods.

Continuous simulation procedures are well suited to the analysis of complex systems which are dependent on the sequencing of flood volumes as the method implicitly accounts for the joint probabilities involved. Application of these methods require more specialist skill than event-based procedures; for example, it is important that the probabilistic behaviour of the input rainfall series relevant to the catchment (either historic or synthetic) is consistent with design rainfall information provided in Book 2, and that the model structure yields flood hydrographs that are consistent with available evidence. Transposition of model parameters to ungauged sites presents significant technical difficulties which would require specialist expertise to resolve. Given these challenges it is presently recommended that the main benefit of continuous simulation approaches is for the extension of flow records at gauged sites with short periods of record, where system performance is critically dependent on the sequencing of flow volumes; if flow data are not available, then it may be appropriate to consider their application to small scale urban environments where runoff processes can be inferred from an analysis of effective impervious areas. Its position in Figure 1.3.2 indicates the degree of accuracy of results that can be expected from this method relative to at-site frequency analysis.

By comparison with continuous simulation models, event-based models are far more parsimonious and more easily transposed to ungauged catchments; it is easier to fit the fewer model parameters involved to observed floods, and their structure has been tailored specifically to represent flood behaviour. However, while such models are easily calibrated and their parameterisation is generally commensurate with the nature of available data, their use generally involves the simulation of floods beyond the observed record. As such, it is necessary to make assumptions about the changing nature of non-linearity of flood response with flood magnitude and trust that the model structure and adopted process descriptions are applicable over the range of floods being simulated. These assumptions introduce major uncertainties into the flood estimates, and this uncertainty increases markedly with the degree of extrapolation involved. This issue is discussed in greater detail in Book 8.

The event-based methods considered in these guidelines generally involve a similar suite of storage-routing methods (Book 5). There are some conceptual differences in the way that these models are formulated, but in general these differences are minor compared to the constraints imposed by the available data. Australian practice has generally not favoured the use of unitgraph-based methods combined with node-link routing models (Feldman, 2000); in principle such models are equally defensible as storage-routing methods, and the strongest reason to prefer the latter is the desire for consistency when used to estimate Extreme floods that are well beyond the observed record, and also for the local experience with regionalisation of model parameters.

Perhaps the greatest choice to be made with event-based models is the adopted simulation environment (as discussed in Book 4). For systems that are sensitive to differences in temporal patterns there is little justification to use simple event methods: the additional computational burden imposed by ensemble event models is modest, and the resulting estimates are much more likely to satisfy the assumption of probability neutrality. However, this additional effort may not be warranted in those urban systems which are dominated by hydraulic controls, and in such cases the most appropriate modelling approach is likely to be a hydraulic modelling system with flow inputs provided in a deterministic manner. Monte Carlo event schemes provide a rigorous solution to the joint probabilities involved, and the solution scheme ensures expected probability quantiles that are probability neutral, at least for the given set of ensemble inputs and distributions used to characterise hydrologic variability in the key selected inputs. For those catchments or systems where flood outputs are strongly dependent on the joint likelihood of multiple factors, it is necessary to adopt a Monte Carlo event approach.

The greatest uncertainties in terms of both flood magnitude and exceedance probabilities are associated with the estimation of Extreme floods beyond 1 in 2000 AEP. There is very little data to support probabilistic estimates of floods in this range, and it is prudent to compare such estimates with empirical analysis of maxima based from national (Nathan et al., 1994) or even global (Herschy, 2003) data sets.

It should be noted that the procedures based directly on the analysis of flood data can readily provide an assessment of uncertainty. Additional uncertainty is introduced when transposing flood information to locations away from the gauging site used in the analysis, and the Regional Flood Frequency Estimation Method (RFFE) is the only method where this is provided in a form easily accessed by practitioners. The Monte Carlo event approach provides an appropriate framework to consider uncertainty in a formal fashion, though this will only provide indicative uncertainties: the greater the degree of extrapolation the greater the influence of uncertainty due to model structure and this is a factor that is not easily characterised. The uncertainty bounds shown in the top panel of Figure 1.3.2 are clearly notional and merely reflect the fact that uncertainty of the estimates increase markedly with event magnitude. It must be accepted that when the above procedures are applied to locations not included in their calibration that the associated uncertainties will be perhaps up to an order of magnitude greater.

Lastly, it needs to be recognised that the ranges of applicability of the different methods illustrated in Figure 1.3.2 are somewhat notional, and that there is considerable overlap in their ranges of applicability. It is thus strongly advisable to apply more than one method to any given design situation, where adoption of a final “best estimate” is ideally achieved by weighting estimates obtained from different methods by their uncertainty. Estimates of uncertainty for flood frequency analyses and regional flood estimates are provided in Book 3, and methods for use with rainfall-based techniques are provided in Book 4, with examples showing how uncertainty propagates through to the design outcome being provided in Book 7. In practice, the information required to assign relative uncertainties to different methods is either limited or difficult to obtain, and careful judgment will be required to derive a single best estimate with associated confidence intervals.

3.5. References

Blazkova, S. and Beven, K. (2004), Flood frequency estimation by continuous simulation of subcatchment rainfalls and discharges with the aim of improving dam safety assessment in a large basin in the Czech Republic. Journal of Hydrology, 292(1-4), 153-172. doi:10.1016/j.jhydrol.2003.12.025

Blazkova, S. and Beven, K. (2009), A limits of acceptability approach to model evaluation and uncertainty estimation in flood frequency estimation by continuous simulation: Skalka catchment, Czech Republic, Water Resour. Res., 45, W00B16, doi: 10.1029/2007WR006726.

Boughton, W. and Droop, O. (2003), Continuous simulation for design flood estimation - a review, Environmental Modelling and Software, 18: 309-318.

Cameron, D., Beven, K. and Naden, P. (2000), Flood frequency estimation by continuous simulation under climate change (with uncertainty), Hydrology and Earth System Sciences, 4(3), 393-405.

Castellarin, A. (2007), Probabilistic envelope curves for design flood estimation at ungauged sites. Water Resources Research, 43(4), pp.1-12. doi:10.1029/2005WR004384

Chiew, F.H.S. (2010), Lumped Conceptual Rainfall-Runoff Models and Simple Water Balance Methods: Overview and Applications in Ungauged and Data Limited Regions. Geography Compass, 4(3), 206-225. doi:10.1111/j.1749-8198.2009.00318.x.

Cordery, I. and Pilgrim, D.H. (2000), The State of the Art of Flood Prediction. In: Parker DJ (ed.) Floods. Volume II. Routledge, London. pp: 185-197.

Feldman, A.D. (2000), Hydrologic Modeling System HEC-HMS Technical Reference Manual. CDP-74B, U.S. Army Corps of Engineers.

Haan, C. and Schulze, R. (1987), Return Period Flow Prediction with Uncertain Parameters. American Society of Agricultural Engineers, 30(3), 665-669. doi:10.1109/IWCFTA.2011.52

Herschy, R. (2003), World catalogue of maximum observed floods. IAHS Publ No. 284, 285 pp.

Kuczera, G., Lambert, M.F., Heneker, T. Jennings, S., Frost, A. and Coombes, P. (2006) Joint probability and design storms at the crossroads, Australian Journal of Water Resources, 10(2), 5-21.

Ling, F., Pokhrel, P., Cohen, W., Peterson, J., Blundy, S. and Robinson, K. (2015), Australian Rainfall and Runoff Project 12 - Selection of Approach and Project 8 - Use of Continuous Simulation for Design Flow Determination, Stage 3 Report.

MGS Engineering Consultants (2009), General Stochastic Event Flood Model (SEFM), Technical Support Model. Manual prepared for the United States Department of Interior, Bureau of Reclamation Flood Hydrology Group.

McKerchar, A. I. and Macky, G. H. (2001), Comparison of a regional method for estimating design floods with two rainfall-based methods. Journal of Hydrology New Zealand, 40(2), 129-138.

Nathan, R.J., Weinmann, P.E. and Hill, P.I. (2002), Use of a Monte-Carlo framework to characterise hydrologic risk. Proc., ANCOLD conference on dams, Adelaide.

Nathan, R.J., Weinmann P.E. and Gato S. (1994), A quick method for estimation of the probable maximum flood in southeast Australia. International Hydrology and Water Resources Symposium: Water Down Under, November, Adelaide, I.E. Aust. Natl. Conf. Publ. No.94, pp: 229-234.

Paquet, E., Garavaglia, F., Gailhard, J. and Garçon, R. (2013), The SCHADEX method: a semi-continuous rainfall-runoff simulation for extreme flood estimation, J. Hydrol., 495: 23-37.

Rahman, A., Haddad, K., Haque, M., Kuczera, G. and Weinmann, E. (2014), Project 5 Regional Flood Methods: Stage 3, report prepared for Australian Rainfall and Runoff Revision Process.

Sih, K., Hill, P. and Nathan, R. J. (2008), Evaluation of simple approaches to incorporating variability in design temporal patterns. Proc Water Down Under Hydrology and Water Resources Symposium, pp: 1049-1059.

Smithers, J.C. (2012), Methods for design flood estimation in South Africa, Water SA, 38(4), 633-646.

WMAwater (2015), Australian Rainfall and Runoff Revision Project 3: Temporal Patterns of Rainfall, Part 3 - Preliminary Testing of Temporal Pattern Ensembles, Stage 3 Report, October 2015.

Weinmann, P.E., Rahman A., Hoang, T.M.T., Laurenson, .E.M., Nathan, R.J. (2002), Monte Carlo simulation of flood frequency curves from rainfall - the way ahead, Australian Journal of Water Resources, IEAust, 6(1), 71-80.

Chapter 4. Data

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4.1. Introduction

Data, in a range of types, is essential for all water resources investigations, especially the topics involving design flood estimation covered by Australian Rainfall and Runoff. This data is needed to understand the processes and to ensure that models are accurate and reflect the real world issues being analysed.

While standard hydrologic data includes rainfall, water levels and streamflow, a range of other data is also useful or even essential for flood investigations. This chapter provides some background on the types of data needed, and specific issues related to each of these.

It also needs to be pointed out that most the procedures and guidelines presented in Australian Rainfall and Runoff could not have been developed without historical data, and often the reliability of the methods presented depends on the extent of data that has been used in its development.

4.2. Background

Because of variability in water resources data (especially in Australia), long historical records are important to ensure that this variability is well sampled. Long records help to ensure that extremes of both wet and dry periods have been sampled.

However, having long term records means that trends in the data may be important. Trends may be natural or human-induced and may be difficult to detect because of variability and the infrequent occurrence of rare events. Trends can result from human-induced climate change, land use changes, or poorly understood long term climate cycles (e.g. related to the Inter-decadal Pacific Oscillation and other large scale phenomena). Careful analysis is needed to ensure that the long historical records are considered in the context of long and short term natural variability and trends.

There are many organisations that collect and maintain data that is useful for flood estimation. Some of these organisations are major authorities that can be clearly identified and have well organised data in accessible formats. However, there is also a considerable amount of data that is harder to find and often valuable information can be found in unexpected locations. This chapter provides information on the types of data that may be useful, sources where this data can be found and the accuracy that can be expected. A useful discussion on the value of hydrologic data, specifically streamflow data, is included in the paper by Cordery et al. (2006).

Routine data collection programmes are important, but it is often valuable to expend some effort in finding and verifying other data for particular projects. It is also important to note that data useful for these projects may be anecdotal rather than formal and often valuable information can be gathered by simply holding discussions with local residents or other stakeholders. Many projects have a consultation programme which can uncover useful information.

As well, specific formal data collection programmes are often needed for particularly large projects, where the scale of the project justifies expenditure on data collection. For example, this type of programme is often carried out as part of environmental impact studies for major projects during the approval process.

4.3. Risks From Inadequate Data

The following comments are taken from the paper by Cordery et al. (2006).

Australia is the driest inhabited continent and has a more variable climate than other continents. As a result water resources in Australia are often scarce and are therefore critical to the nation’s prosperity. At the other end of the scale, large floods often cause devastating damage to property and endanger lives. While present generations are benefiting from the data collection activities of our predecessors, it is our responsibility to ensure that future generations are not disadvantaged by the changes we are implementing now. Data collection is about reducing the risks and increasing the benefits the current and future generations receive from the expenditure of the limited funds available for water management.

Water resources data are used for:

- Flood warning (e.g. the Nyngan floods);
- Groundwater and dry-land salinity assessment and management (e.g. throughout the Murray Darling Basin and much of WA, the Great Artesian Basin and inland sub-artesian aquifers);
- Drinking water quality (e.g. coliform counts as health indicators);
- Design of bridges, dams, stormwater and sewer systems;
- River water quality (e.g. blue-green algae outbreak in the Darling River, habitat protection);
- Water supply for urban and rural communities (e.g. water restrictions and new dams);
- Irrigation for agriculture (e.g. the cap on extractions from the Murray Darling Basin);
- Assessing climate change and its effects on future availability of freshwater;
- Extreme flood estimation (e.g. Warragamba Dam spillway upgrade);
- Water trading – agreed volumes and timing must be reconcilable, and be measured accurately, compliance with licence entitlements; and
- Development of water plans and policies.

Considering the specific concerns for Australian Rainfall and Runoff, inadequate data or the lack of data leads to uncertainty in the results of the analysis and will tend to require additional freeboard allowance for example to compensate for the uncertainty. While there are available procedures that are regional specific and can be implemented on ungauged catchments, there will be more uncertainty in these applications and therefore an increase risk in the flood estimation application. Practitioners need to utilise as much local information, even if this is anecdotal and limited, as possible to reduce this risk.

4.4. Stationarity

Detection of changes in river discharge and magnitude of flood peaks, whether it is abrupt or gradual change is of considerable importance, being fundamental for planning of future water resources and flood protection (Kundzewicz, 2004). Generally flood analysis and planning design rules, including data collection programmes, are based on the assumption of stationary hydrological data sets. If the stationarity assumption is proved to be invalid through global climate change then the existing procedures for designing water-related infrastructures will need revision. This has been recognized in the US with increased emphasis on maintaining stations with long data records (National Research Council, 2004). Long data sets and ongoing analysis are essential to promote accurate design of systems to perform adequately for their design probability and not be over designed resulting in higher costs or under-designed resulting in large damage bills, loss of life and perhaps ultimate failure of structures with resultant community destruction.

A range of human activities including man-made structures such as dams, reservoirs and levees can change the natural flow regime. Land cover and land-use changes including deforestation and urbanization controls many facets of the rainfall–runoff process increasing the peak flows and increasing the amount of runoff. Water conveyance in rivers is altered by river regulation measures (such as channel straightening and shortening, construction of embankments, construction of weirs and locks) or the rehabilitation of rivers with increased stabilisation using trees and logs to provide a better environment for native species. Abstractions from river systems can cause them to run dry and further change the natural channel system and henceforth impinge on the magnitude of larger floods stage height by the considerable amount of debris in the rivers.

Hydrologic data series have generally been considered to be stationary series i.e. there are no long-term shifts in the time series statistical parameters. However, it is recognised that with the “greenhouse effect” analyses might need to take into account the non-stationary effects when performing hydrologic designs. There is therefore a demonstrated need to continue data collection to avoid potential large errors in hydraulic structures design and water resources management due to inadequate streamflow data (Wain et al., 1992).

All flood investigations need to consider the potential for non-stationarity in any data applied to the project, and make appropriate adjustments as required.

4.5. Hydroinformatics

4.5.1. Introduction to Hydroinformatics

An important component for prediction of design flood characteristics is the consideration of the data available for the purpose of predicting both, the magnitude and probability of a flood characteristic. Since the publication of the previous edition of Australian Rainfall and Runoff (Pilgrim, 1987), the increasing computational power available has seen changes in availability and perceptions of data. These changing perceptions resulted in development of hydroinformatics as a conceptual framework for various techniques and approaches to deal with information about water in an electronic format.

Though Abbott (1991) first proposed the term "Hydroinformatics" as a generic term describing the utilisation of information and data about water, the most encompassing and concise definition was presented by Meynett and van Zuylen (1994) who stated:

> ... hydroinformatics deals with the electronic knowledge encapsulation of various sources of information related to the hydro sciences.

With this definition, it is clear that the term 'hydroinformatics' covers a wide range of subject areas that are beyond the classical hydrological and hydraulic sciences involved in design flood prediction and management. This definition also includes data and information from the political, social, economic and legal spheres relevant to design flood events. As suggested, though the scope of hydroinformatics is extensive, however, only those aspects relevant to prediction of design flood characteristics will be discussed in this chapter.

4.5.2. Components of a Hydroinformatics System

Since the specifications of each hydroinformatics system are different and their components will also differ for each application, it is impossible to define all the components that together will constitute a system, however, the concept is that a hydroinformatics system deals with data processing in hydro-environmental sciences. Therefore, any software that assists in this regard can be considered to form part of a hydroinformatics system.

Generally, for a system concerned with the prediction of design flood quantiles, the following components are expected :

- Databases for the storage, retrieval and display of spatial, temporal and statistical data;
- Models for prediction of design flood quantiles using the information contained in the relevant databases;
- Models for generation of data about catchment response to storm bursts or complete events; and
- Decision support systems for enhanced modelling and analysis.

This guide does not discuss all the aspects of a hydroinformatics system, rather the purpose of this guide is to introduce the concept of a hydroinformatic system for design flood estimation in sufficient detail for design flood analysts. Further information on development in and application of hydroinformatics systems can be found in Vathananukij and Malaikrisanachalee (2008), Malleron et al. (2011), Hersh (2012), Popescu et al. (2012), and Moya Quiroga et al. (2013).

4.6. Data Categories and Issues

4.6.1. General

There are two broad groups in which hydrologic data can be categorised, as follows:

- Routine
- Project specific

Routine data collection includes the standard and widely available data, such as streamflow or rainfall data collected on a routine basis by major government agencies such as the Bureau of Meteorology. This data is collected to provide a long term understanding of Australia’s climatic conditions for a representative selection of sites throughout the country. These stations are the basis of many flood estimation procedures and for projects, though the data is appropriate for many other applications.

Project specific data is collected especially for a particular project, and may include observations for major floods in the project area and other specific information to assist in a particular project.

4.6.2. Data Source Organisations

Data can be obtained from a wide range of organisations and individuals, and effort expended in sourcing and checking all available flood data and information is worthwhile. Data can be sources from a number of immediately obvious organisations, but can also be found from others that may not be so obvious.

Major water authorities, such as the Bureau of Meteorology and state water agencies are immediately obvious sources, and these organisations are expected to hold most of the data from formal data collection programmes. These agencies generally have well designed websites, where data can be reviewed and downloaded, and almost all data required for flood investigations can usually be downloaded from these agency websites for no charge.

Other sources include:

- Local authorities. Councils are responsible for planning process and flooding is an important constraint to their planning. Councils therefore usually hold historical data on flood levels as well as other observations.
- Transport agencies. The major state government road and rail agencies, as well as privatised road and rail organisations usually hold extensive data on flooding as it affects their infrastructure.
- Other government agencies. Activities of other agencies such as those responsible for the primary industries, environment or mining are impacted by flooding and they will often hold flood or other meteorological data relevant to flooding.
- Commercial organisations. Mining or agribusiness companies require flood data as it affects their activities and may hold relevant data.
- Farmers and graziers. The weather is critical to agricultural industries and many farmers operate a raingauge and can at least provide data for major storm events, but they may also hold flood records as they affect their irrigation performance for example.
- Individuals. Many individuals have an interest in flooding especially if it affects them so flood levels and other observations can often be obtained from individual property owners.
- Others. There may be specific stakeholders who could supply flood data for a particular flood investigation, and these can vary depending on the actual project and location.

In general therefore, it is important to search widely for flood data during projects. Even anecdotal information will usually be of value in setting model parameters and improving local understanding of flood conditions.

4.6.3. Data on Historical Events

This information is particularly important for most projects, and can often provide a significant improvement in the quality of the analysis. While data on historical floods may be difficult to obtain at times, efforts expended in finding and analysing this data is extremely valuable.

There are three types of data referred to here. These are:

Significant events.

If a major event occurs, it is important for the Bureau of Meteorology, Council or other appropriate agency to collect as much relevant information as possible soon after the event and publish this, even if only in an internal report. Because major events occur rarely and unexpectedly, it is often difficult to mobilise the resources in time and appropriately. As well it may not always be obvious that this data will be useful, so there may not be an immediate interest in the data collection. The Bureau of Meteorology produce reports following major events and these reports usually contain information that is very helpful in particular projects.

Historical events.

Where especially significant events have occurred in past, there are often historical records of the event. These records may be in reports by relevant government agencies, but often there may be useful information in newspaper reports, historical societies or museums or information can be gathered from old long term residents. Particularly significant events such as the Clermont storm of 1916 and the Brisbane floods of 1893 have good published data, but other events may be more difficult to locate.

"Routine" flood data.

As well as the major events noted above, data on more routine (though still large) events can be sourced from discussions with residents and other stakeholders. This data is usually descriptive, but often actual flood levels can be surveyed based on the data held by residents and flood marks on buildings and elsewhere. This data is especially useful if there has been a major flood in reasonably recent times, and local residents can recall details. Photos or videos can be obtained as part of these programmes.

The accuracy of this type of data may be extremely variable and careful review and checking is essential. The requirements for checking are difficult to specify, but the checks should involve review of the consistency between individual data points and a general check of "reasonableness".

Usually this type of data is of variable quality, but with careful collection and checking, is almost always very valuable in implementation of projects.

As well as "numerical data", other less formal data can be collected for historical events. These can include photos or videos taken during the flood or eye witness descriptions and accounts. While this type of information may not be directly applicable for model calibration, it is invaluable in many applications to ensure that the model is representing the general flow conditions and distribution.

This type of data is often sourced from local residents during consultation programmes, when the flood specialist specifically searches for it.

4.7. Discussion on Hydrologic Data Issues

4.7.1. Data Types

4.7.1.1. General

Data is defined as the value of qualitative or quantitative variables. While this definition is simple, the interaction of data with knowledge and data warrants discussion, particularly because the concept of the terms data, information and knowledge frequently overlap each other.

The main difference between these terms is in the level of abstraction being considered. Data is the lowest level of abstraction, while information is the next level, and knowledge is the highest level among all three however, data on its own carries no meaning. For data to become information, it must be interpreted and should take on a meaning. For example, the height of Mt. Everest is considered generally as 'data', but a book on the geological characteristics of Mt. Everest may be considered as 'information', while a report containing practical information on the best way to reach the peak of Mt. Everest may be considered as 'knowledge'. This distinction between the terms is consistent with Beynon-Davies (2002) who uses the concept of a sign to distinguish between data and information; data are symbols while information occurs when symbols are used to refer to something.

In the following discussion of types of data, the lowest level of abstraction is used, namely data has a value but no meaning.

4.7.1.2. Deterministic

Deterministic data can be defined as data that has a unique value in spatial and temporal dimensions. There are many examples of deterministic data used in prediction of design flood quantiles; these examples include Digital Elevation Model (DEM) of the catchment, the surface roughness parameter, and the continuing loss rate parameter.

4.7.1.2.1. Probabilistic

In contrast to deterministic data, probabilistic data does not have a unique value, rather it has a range of values described by a statistical relationship. Each time a data value is sought from probabilistic data, the data value will be different. An example of a probabilistic parameter would be the continuing loss rate for use in a Monte Carlo simulation; in this example, the continuing loss rate will be sampled from distribution of potential continuing loss rates, with each sample likely to differ from previous samples.

4.7.1.3. Spatial

Data can be unique to a point or cover a spatial extent. Additionally, the data may vary in the spatial dimensions but be invariant with time. There are many examples of spatial data types in design flood prediction, including:

- Soil types;
- Spatial patterns of rainfall; and
- Flood surface elevations.

4.7.1.4. Temporal

Temporal data, in contrast to spatial data, consists of data that varies in the time dimension but, usually, has a fixed location . There are many examples of temporal data types in design flood prediction, including:

- Temporal patterns of rainfall; and
- Historical flood hydrographs.

4.7.1.5. Meta-data

For optimal utility in use of data, it is imperative that potential users have the possibility of tracing the data passage stored in an electronic database to its initial source. Questions such as “How were the values obtained?”, “What is the reliability of the values?”, “What editing of the data has occurred?” are vital in assisting the user to interpret the data in a manner appropriate for resolution of the issue under consideration. The development of hydroinformatic systems offers the possibility of facilitating access to meta-data and enhancing the utility of data. The inclusion of meta-data, therefore, is an essential and necessary aspect for suitable use of data in a hydroinformatic system.

A further example of the utility of meta-data for interpretation of data is obtained from consideration of the data necessary for floodplain management. It is possible that a review of the meta-data contained within the hydroinformatic system used for flood management of the catchment may result in the finding that all data within the hydroinformatic system was derived from application of catchment modelling systems and that complementary monitored data was not available. The interpretation of the stored data, therefore, will be different from what would have been the case if the meta-data were not available and it had been assumed that the data were from catchment monitoring.

It is worth noting that prior to the widespread availability of computerised data (i.e. hydroinformatic systems), the analyst preparing the recommendation for freeboard probably would have been aware of the data sources (i.e. the meta-data) and, therefore, would have incorporated this knowledge into the interpretation and ultimate recommendation. Consequently, the inclusion of meta-data in the hydroinformatic system does not generate new knowledge in itself but merely incorporates knowledge currently available only in a non-electronic form.

4.7.2. The Data Cycle

Fundamental to the concept of hydroinformatics is the management of data and its passage from the time it is generated to the time when it is used or presented to stakeholders and other interested parties. During this time, data can be considered to pass through a number of conceptual components. The passage of data through these components is not uniform and linear, rather will pass through the cycle in a random and nonuniform manner. The passage of the data and the components through which it passes, can be considered as the data cycle (Ball and Cordery, 2000).

Conceptually, the data cycle is analogous to the hydrologic cycle where the passage of data through the data cycle can be considered analogous to the passage of water through the hydrologic cycle. Also, similar to the hydrologic cycle, the data cycle can be considered in a systems format with the data flowing between different components.

If the data necessary for prediction of design flood characteristics is considered in this manner, then it is apparent that the components of the data cycle are relevant to the design flood problem. Hence, the concepts associated with hydroinformatics and the data cycle are relevant to the prediction of design flood quantiles.

One of the conceptual views of components forming the data cycle is shown in Figure 1.4.1. The conceptual components shown in the figure are Generation, Editing, Storage, Analysis and Presentation. Also, as indicated , there is a circularity in the flow of information, which arises from analysis of data resulting in generation of new data that needs to be edited and stored in a manner similar to previous data. Considered in this manner, an individual component within a hydroinformatic system is both, a supplier and the data user.

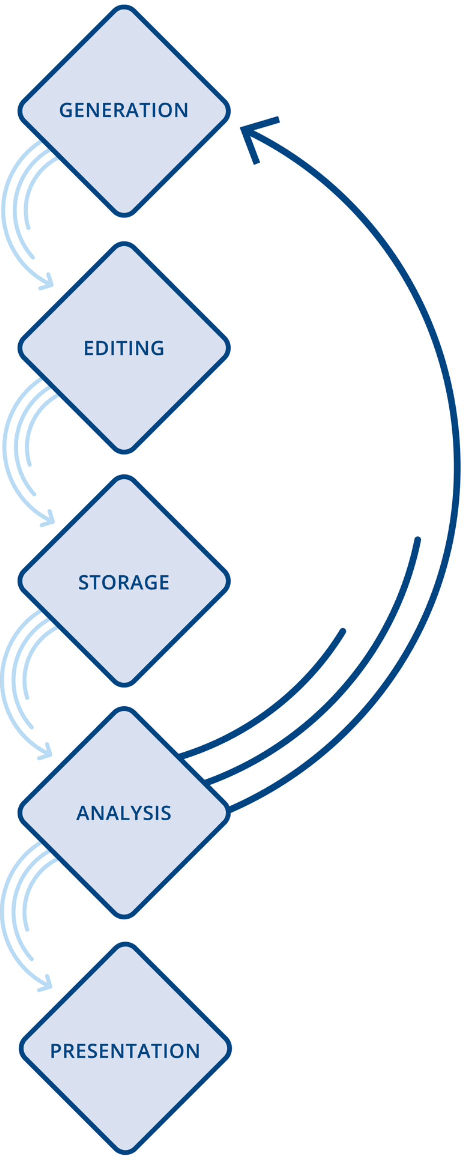


Figure 1.4.1. The Data Cycle

Within each of these conceptual components of the data cycle, the pertinent aspects are:

- *Generation* - In this component the data is sourced; this can be restated as this is the component where the data is created or collected. Furthermore, it is the component where data is recognised relevant for prediction of the design flood characteristics.

  For example, in a catchment monitoring program aimed at collecting discharge data, the necessary steps, as discussed by Chow et al. (1988), would be:

  - sensing the phenomenon;
  - recording the value of the phenomenon; and
  - transmission of these values to a storage repository. This storage depository may be centralised or distributed according to the needs of the stakeholders involved.

Further details on data creation through monitoring programs are presented Book 1, Chapter 4, Section 12.

In addition to the data generation through technical approaches, there are other methods of data generation, where data can be collected through social surveys, census surveys, and historical reviews for example. This data, similar to the technical data, will require management using the concepts of hydroinformatics and the data cycle.

- *Editing* - An important aspect of data is knowledge of its accuracy (sometimes referred to as its uncertainty) and original source. Prior to insertion into a database, it is necessary to define these parameters; in other words, the relevant meta-data has to be attached to the data. The term meta-data is used here to describe the background material about the data which is referred to sometimes as the data about the data. Meta-data is discussed further in Book 1, Chapter 4, Section 7.

  For monitored data, items of primary relevance include issues regrading how the data was observed, the reliability of monitoring (for example, the sensitivity of the sensing equipment, the robustness of the rating table for monitored discharges, the detection limit of contaminants for water quality constituents), and editing changes to the data and the philosophy behind these changes. These meta-data are of great importance for catchment monitoring since at least some of the monitored data will be inaccurate; in other words, some of the monitored data will contain undiscovered errors.

  In a similar manner, data generated by catchment modelling systems needs to be defined by the software (and version) used, the input data inclusive of adopted parameter values or distribution of parameter values. It is should be noted that input data covers both the parameters necessary for operation of the software and the data necessary for implementation of the modelling system. Therefore, one can conveniently state that editing of data generated from catchment modelling systems, i.e. the attachment of meta-data, should be sufficient to define how the data was generated and enable replication.

  The step involving data editing is a vital part of the data cycle and should prioritised above data insertion into relevant database and its subsequent usage by others not involved in its generation. The inclusion of the meta-data and its availability to future users is becoming increasingly important as the availability of digital data increases and data users become more remote from the generation of the data.

- *Storage* - The storage of the data is performed in this component of the data cycle. In general, the storage of data will comprise the insertion of the data into a digital database. It is important to note that the manner of data storage should ensure that its retrieval is both practical and feasible. If retrieval is not easy, there is no addition to the data available for design flood estimation.

  There are many different forms of data stored in a database which in turn influences the data storage design. Commonly, spatial databases are referred to as Geographic Information Systems (GIS) while databases used to store temporal data can be referred to as a Time-Series Managers (TSM). These computerised storage facilities have superseded, in general, the previous techniques based on data storage through maps and charts. There are a large number of alternative GISs and TSMs that can be used for data storage. It is not the purpose of Australian Rainfall and Runoff to recommend a particular GIS or TSM but rather to note their use for storing data relevant to design flood estimation.

  Since 2008, the Bureau of Meteorology (BoM) has been responsible for delivering water data throughout Australia. As part of this role, the Bureau of Meteorology has been collecting water data from more than 200 organisations across the nation and is using this data to report on water availability, condition and use in a nationally consistent way. To facilitate this role, the Bureau of Meteorology is building the Australian Water Resources Information System (AWRIS) as a secure repository for water data and as a means to deliver high quality water data to all Australians.

The aim of AWRIS is to allow the Bureau of Meteorology to process and publish water data in new and powerful ways. The Bureau of Meteorology will be able to merge historical water data records with current observations to suit a variety of user needs. By spatially enabling this data we will be able to query and report the data in many different ways. Data stored in AWRIS will be delivered to the web, to mobile devices and various hydrologic forecasting systems to be operated by the Bureau of Meteorology.

- *Analysis* - It is common that analysis of data will be required. The analysis techniques form this component of the data cycle. The steps involved in this component can be summarised as data retrieval, and data usage. It is worth noting that the data obtained from the analysis could be considered as part of the data generation component. Hence there is some similarity between the generation and analysis components.

  There are many alternative analysis techniques. For design flood estimation purposes, the most commonly used analysis techniques would be statistical modelling (for example, Flood Frequency Analysis) and catchment response modelling using a catchment modelling system. Both of these techniques result in the generation of additional data that, in turn, requires editing and storage.

- *Presentation* - The final conceptual component is the presentation component. Within this step, the stored or analysed data is presented in a manner that is understandable to relevant stakeholders. The technical level of the presented data would not be constant for all presentations but, rather, would vary with the technical expertise of the audience. The important point about the presentation of data is that it is presented in a manner that is clear and precise for the audience.

4.8. Hydrologic Data

This section has an outline of the types of data that is needed for hydrology and hydraulic analysis required for flood estimation and the issues associated with each type.

The data types that are needed are as follows, with discussion or each in the following sections.

- Rainfall;

- Other precipitation types;

- Water levels;

- Streamflow;

- Catchment data, including topography, survey, digital terrain, land use and planning data; and

- Other hydrologic data, including tidal information, meteorological, sediment movement and deposition and water quality.

This data needs to be collected, reviewed for completeness and accuracy and then archived and disseminated to practitioners as required. Discussion on specific details is included below.

4.9. Rainfall Data

4.9.1. Overview

Rainfall is a primary data input for almost all water resources projects, and rainfall data forms the basic input to the development of the rainfall chapters in "Australian Rainfall and Runoff" as well as a key input to other components.

The Bureau of Meteorology is the primary agency responsible for collection of rainfall data in Australia, but there are many other agencies which have significant records of rainfall data. The other agencies include local authorities and water agencies, but some organisations have particular local data programmes that may be useful in specific projects. As well rainfall data can be collected from various sources for major historical floods as discussed further below.

In many major flood events, it is often valuable to look for unofficial rain gauges where data has been collected by members of the public. In rural areas, most property owners have rain gauges and they are also not unusual in towns and cities.

Data endorsed by the Bureau can be regarded as accurate, but some checks for consistency and the reasonableness of the data should also be carried out. In particular, tests for missing (accumulated) data need to be considered but it is also possible that gauge overflows mean that the larger events are not well measured. Data from other agencies may be also of a high standard, but these agencies sometimes have poorer quality data. More careful checks are needed on this data. Data collected at unofficial rain gauges operated by members of the public may be sometimes of very poor quality, with poor exposure for example, and records from these sources must be checked very carefully. However the value of this data means that it is often worth further analysis to ensure that useful data is not discarded. Data from unofficial gauges is especially important for major events where it can be used to supplement information from official gauges.

Most publicly available rainfall data should be available through the Bureau of Meteorology’s AWRIS database.

The types of rainfall data that may be useful include:

- Daily rainfall records; and
- Pluviometer records.

Normally data endorsed by the Bureau of Meteorology can be relied upon. However, users should check the data for consistency and logic, before application. In particular, tests for missing or accumulated data need to be considered, along with assessing the potential for gauge overflows.

4.9.2. Rainfall Observations

The standard instrument for manual measurement of rainfall is the 203 mm rain gauge (see Figure 1.4.2). In essence, this instrument is a circular funnel, with a diameter of 203 mm and the top located 0.3 m above the ground surface,that collects the rain into a graduated and calibrated cylinder. Any excess precipitation is captured in the outer metal cylinder. Most manually read gauges are used for daily observations.

Daily rainfall is nominally measured each day at 9:00 am local time. At most rainfall sites, observations are taken by volunteers who send in a monthly record of daily precipitation at the end of each month. A subset of observers at strategic locations, as well as automatic weather stations, send observations electronically to the Bureau of Meteorology each day. Very few stations have a complete unbroken record of climate information. Missed observations may be due to observer illness or equipment failure. If, for some reason, an observation is unable to be made, the next observation is recorded as an accumulation, since the rainfall has been accumulating in the rain gauge since the last reading.

Figure 1.4.2. Standard Rain Gauge (Source: Bureau of Meteorology)

An alternative to the manual measurement is to use a continuous recording rain gauge resulting in either an analogue chart record or a digital record. While some chart recorders remain in operation, the more common form of continuous rain gauges is the Tipping Bucket Rain Gauge (see Figure 1.4.3). Like the manual rain gauge, the aperture of the funnel for a TBRG is 203 mm.

Figure 1.4.3. Tipping Bucket Rain Gauge (Source: Bureau of Meteorology)

Advantages of the TBRG are claimed to include unattended, automatic operation, and the ability to record the rate at which the rain is falling. Operation of a TBRG is based on the generation of an electronic pulse when the water volume collected in the bucket results in bucket tipping. While the usual volume of water collected is equivalent to a depth of 0.2 mm, some early TBRGs required a depth of 0.5 mm before the bucket would tip. When analysing data from TBRGs, users should check the bucket size to ensure the validity of the analysis; this information should be available from the meta-data attached to the recorded data.

Traditionally rainfall is measured to the nearest 0.2 mm (prior to 1974 records were in Imperial units and measurements were to the nearest 1 point, approximately 0.25 mm). However, in recent years some observations have been reported to 0.1 mm. Hence, users check the meta-data attached to the data records to note the measurement accuracy rather than the inferred accuracy from the database records.

The Bureau of Meteorology undertake a number of quality control processes to detect errors in the rainfall data forwarded from the many volunteer and professional readers. This data checking includes:

- Values that extend beyond what is considered realistic;
- Inconsistent observations (for example, high rainfall combined with clear skies); and
- Discontinuous or abrupt changes in values over a short period of time.

While the Bureau of Meteorology undertakes these checks it is recommended that individual users ensure that their rainfall data is suitable for purpose. This may entail undertaking additional quality control processes.

4.9.3. Review of Rainfall Data

While rainfall data is frequently regarded as reliable and accurate, there are some issues with the accuracy and consistency of rainfall data and these need to be considered while applying data to practical applications. Issues often encountered are.

- Accumulated records. Rainfall data, especially from daily read gauges may have missing days of record. In some cases, these missing days are simply not recorded while on other occasions, the total for a number of days is accumulated. This occurs since thee rainfall is collected in the raingauge and several days record are recorded on a single day at the end of the accumulated period. These records need to be reviewed in conjunction with records from neighbouring gauges and adjustments made as necessary. Accumulated records may give an excessively high daily record for the day where the records are accumulated.
- Missing data. In some cases, for both daily read and continuous gauges, there may be missing periods of record. In this case, the record should be reviewed carefully in conjunction with records from neighbouring catchments and appropriate adjustments made.
- Gauge quality. Rain gauges operated by the Bureau of Meteorology are expected to meet the Bureau of Meteorolgy’s standards, however other gauges, especially privately operated gauges which may be used to supplement rainfall records for major events, may not meet the Bureau of Meteorolgy’s stringent standards. Where privately operated gauges appear inconsistent with nearby stations, the siting of the gauge needs consideration and it may be necessary to remove the gauge from the analysis.

4.9.4. Rainfall Databases

4.9.4.1. Introduction

The Bureau of Meteorology has developed a number of databases for storage of rainfall data and its meta-data. These databases include:

- Australian Data Archive for Meteorology (ADAM);
- Site Meta-data (SitesDB); and
- Australian Water Resources Information System (AWRIS).

4.9.4.2. Australian Data Archive for Meteorology

The Australian Data Archive for Meteorology (ADAM) stores meteorological observations from observing systems over mainland Australia and from neighbouring islands, the Antarctic, ships and ocean buoys that are operated by the Bureau of Meteorology. It also stores a limited number of observations from other local and international sources to support research and improve Bureau of Meteorology services.

The most common observation type stored in ADAM is daily rainfall. Dating back to the mid-1800s, these total more than 200 million records from a network of over 16 000 locations. Other types of weather data that are stored in ADAM include air temperature, humidity, wind velocity, sunshine, cloud cover, soil temperatures, upper atmospheric wind and temperature, and observed weather phenomena (for example, thunder, frost and dust).

To support this large database, the ADAM system contains supporting database tables and software tools required to enter, retrieve and quality control data efficiently. A set of detailed rules and procedures ensure consistent treatment of information.

4.9.4.3. Site Meta-data

Meta-data about the Bureau of Meteorology’s rainfall stations is stored in 'SitesDB'. It contains meta-data for each of the Bureau of Meteorology operated rainfall stations and includes, as a minimum, the following information:

- Rainfall station name and number;
- Rainfall station location in latitude and longitude;
- Rainfall station elevation; and
- Details of the current instrumentation.

However, for many stations the following meta-data are available also:

- Maps showing location of rainfall station;
- Schematic of rainfall station layout;
- Photos of rainfall station;
- Photos for each of the four main compass points showing siting, clearance and proximity to trees, buildings and other factors likely to influence measurement of rainfall;
- History of instrumentation installed at site; and
- Record of dates of site visits, maintenance undertaken, problems identified and resolution adopted.

4.9.4.4. Australian Water Resources Information System

The Bureau of Meteorology is building the AWRIS as a secure repository for water data and as a means to deliver high quality water information to all Australians. Under the Water Regulations 2008, the Bureau of Meteorology receives information about river discharges and groundwater levels, water volumes in storage, water quality in rivers and aquifers, water use and restrictions, water entitlements and water trades. The intention is that AWRIS will store and manage this data in a central database.

To achieve this aim, AWRIS is a powerful hydroinformatic system capable of receiving, standardising, organising and interpreting water data from across the nation. The Australian Hydrological Geospatial Fabric (also known as the Geofabric refer to Book 1, Chapter 4, Section 13) is a vital component of AWRIS. It is a specialised Geographic Information System that enables a spatial context to the data stored within AWRIS. With this spatial context, the utility of water data of the data will be enhanced through ease of access. Additionally, the Geofabric encodes the spatial connections and relationships between most of Australia's hydrological features including rivers, dams, lakes, aquifers, diversions, supply channels, drains and monitoring points. Distribution of the data stored in AWRIS is through the Bureau of Meteorology website and Water Online.

4.9.4.5. Gridded Rainfall Data

In addition to the recorded rainfall data from rain gauges located in and near the catchment, the Bureau of Meteorology publish a grid of daily rainfall data for the whole of Australia covering a period from 1900 to date. This is a component of the Australian Water Availability Project (AWAP) (Jones et al., 2007; Raupach et al., 2009). This grid is at a resolution of approximately 5 km (0.05 degrees) and includes daily rainfall value for each grid cell for each day from 1900. The quality of the grid points varies depending on the period of interest since there is a better coverage of gauges in more recent times. The quality also varies depending on the location, with less accurate records for locations with high rainfall gradients and for less populated regions where there is a more sparse gauge density.

4.9.5. Application of Rainfall Data for Flood Estimation

Rainfall data is a critical input to the development of ARR and is also essential in many flood applications, with two principal applications.

Firstly extensive statistical analysis of rainfall data has been carried out to prepare the Intensity Frequency Duration (IFD) input applied to many assessments. Details of the rainfall data analysed for the IFD development is discussed in Book 2, Chapter 3.

Secondly rainfall data is applied for analysis of historical events for flood analysis, and in this application, recorded rainfall data is required for these historical events.

4.10. Other Precipitation Types

Other sources of precipitation include snow, hail or dew. These are usually a relatively minor component of the water balance in Australia, but there are some locations and occasions where this data may be of interest or value for particular projects.

In parts of Australia, snow may contribute a significant amount of precipitation affecting water resources, but this is not common.

The Bureau of Meteorology and specialist agencies in mountainous and southern regions collect this data, and use it for specific studies and supply it on request.

4.11. Water Levels

4.11.1. Overview

Water level data is a principal data type, and as well as being used in its own right, is also used to calculate streamflow data.

A major source of water level data is at formal stream flow stations operated by the major water authorities. This data is usually converted into streamflow data as discussed further below, but there are some locations where only water level data is collected or published. Water authorities publish data and it is usually freely available. The published data usually has an indication of the accuracy and completeness, but some checking is needed.

In addition, there are many stations, especially those operated by the Bureau of Meteorology and local authorities, mainly for flood forecasting and warning, where stream flows are not calculated and water levels only are available. The larger agencies usually make this data available, sometimes on line.

Water level data may be in the form of continuous records monitored by an automatic recorder or as manually read records. Most of the earlier records were manually read at staff gauges, but many of these are now replaced by automatic water level recorders. Manually read records were usually recorded once a day with supplementary more frequent readings during flood events. Because of the rapid response of many streams, the manually read records may not provide the peak levels and may even totally miss short duration flood events. Manually read records are usually better quality for large slowly responding streams and this data can be used with confidence, but smaller catchments may be significantly in error. More often than not, manually read records show smaller flood peaks and lower discharges than automatic recorders. However practically all records from before the 1960s are manually read, so this data forms the only available information for long term stations. Therefore data from manually read stations is usually the only available record and has to be used, but careful consideration is needed to make sure the records are interpreted correctly.

In addition to the formal water level records, informal records can also be obtained usually following a major flood event. These records are usually obtained by a Council or other stakeholder who sends surveyors on-site soon after an event to survey flood marks to indicate the maximum water levels reached. This data provides an indication of the variation of water levels across the floodplain and an indication of the flow patterns. The quality of this data may sometimes be questionable, and the records need to be carefully checked. These checks can include checking for consistency and reasonableness as well as a review of the reliability of the agency or person who has collected the data. When this type of data is collected, it is important that the records include careful descriptions of the circumstances of the collection and an indication of the expected accuracy.

Common concerns with this data is the level of observed debris marks, whether the water levels have been collected at the peak level of the flood and the source of the water level, either local drainage or backwater for example. Therefore while very useful data can be obtained, it must be carefully reviewed otherwise the data may lead to incorrect conclusions in the resulting analysis.

However water levels are often only used as the source of streamflow or discharge data, as discussed below, and while water levels are useful in many applications, streamflow data is usually of far greater value for many water resources studies.

4.11.2. Historical Flood Level Data

4.11.2.1. Continuous Water Level Recorders

Continuous water level recorders measure water levels at nominated intervals and, where a rating curve (stage-discharge relationship) exists, these can be converted to discharge. Flow is derived from stage using a stage-discharge relationship and it is critical that maximum gauged flow is known so that the extent of extrapolation underlying the ‘recorded’ flow is clear (refer to Book 1, Chapter 4, Section 12). These records are very important as, if intact, they will show the complete hydrograph (i.e. the rise, peak and fall of the flood). Historical records for continuous water level recorders are typically stored by government agencies and one needs to be careful with the datum of these records as may not be to AHD (Australian Height Datum) and some conversion may be required. In case of large events, these recorders can fail and the data needs to be inspected for 'flat' areas, which may indicate failure of the gauge or they may rise steeply in case of a landslip occurs. Typically, each stage record has an accuracy code assigned and these should be noted before use.

4.11.2.2. Maximum Height Gauges

Maximum height gauges simply record the peak flood level reached during a particular event. Again, data is often held by a government agency and one needs to be careful while converting the gauge datum to AHD. Failure of these gauges is difficult to detect as they are simply recording the peak level, and if the gauge fails before the peak of an event, it may still provide a 'peak level' value, which will refer the flood level reached prior to the peak at the time of gauge failure. Time of peak is sometimes also available, however, it is recommended that this is checked to ensure that the peak was recorded at approximately the correct time.

4.11.2.3. Peak Level Records

If the flood event has been of a significant nature, it is likely that stakeholders have been able to collect some actual flood levels at a variety of locations. This is typically done by mobilising agency staff to place markers (paint, stakes, nails, surveyor’s tape) either indicating maximum flood extent (e.g. spray paint on a road, stake in ground) or peak flood levels (e.g. nail in a tree). Ideally, each marker should have the time and the staff member’s name recorded at the marker site. Following the event, surveyors can measure *x,y* location data and z flood level data at each of these markers. It is also useful to photograph the site and to record ground level. Surveyors should also include the time at which the markers were placed, by whom and type (e.g. nail in tree) in their meta-data. Residents often also record peak flood levels, particularly if the flood has inundated any buildings on their property. Post event flood levels can be collected by residents by a questionnaire and reliable marks surveyed. An assessment as to the reliability of these levels can only be made after viewing the marks themselves and noting the care with which the recording has been made. Have different event dates been recorded by the resident or is the resident relying on memory to determine one event from another? Has the location of the marks changed in any way since the record was made? For example, if the marks are made near the front door, has the house been raised at any time since? Detailed discussion with the resident can often unearth important details otherwise unknown.

4.11.2.4. Debris Marks

Debris marks are a typical means of measuring the maximum flood level and are best measured as soon as possible after the event, when the debris or scum line is still fresh. This ensures that the mark is attributable to the event of interest and has not been subsequently degraded.

Debris marks can be inaccurate for a number of reasons. They can be influenced by dynamic hydraulic effects such as waves, eddies, pressure surges, bores or transient effects, which may not be accounted for in a hydraulic model. For example, if the debris mark is located within a region of fast flowing floodwater it is possible that the floodwater has pushed the debris up against an obstacle, lodging it at a higher level than the surrounding flood level. More common though is the fact that debris often lodges at a level lower than the peak flood level. The reason for this is that for debris to be deposited it needs to have somewhere to lodge and this elevation is not always at the peak flood level. For example, the classic place for debris lodgement is a barbwire fence with horizontal strands of wire. If the flood level almost reached the top strand of barbwire, debris will not lodge in the top strand but rather on the second from top strand, which may be about 0.3 m lower than the peak flood level. It is recommended that the surveyor be asked to record as much information as possible about the mark itself (e.g. debris on barbwire fence spacing 0.35 m) so the modeller is able to consider reasons for discrepancies in the calibration process, if they arise.

4.11.2.5. Anecdotal Information

Anecdotal information is usually qualitative in nature but can be very valuable in determining flow behaviour and subsequently verifying that the flood analysis represents these observations in the hydraulic modelling undertaken. Photograph and video evidence can also be beneficial in this regard and can often assist long-term residents remember details of historical floods long past. The flood modeller will need to be mindful of the fact that memories can sometimes fade or be skewed by other events that have occurred particularly when several floods occur close together. In addition, information providers may not be able to provide unbiased information due to a vested interest (e.g. pride or financial gain etc) in the level to which an historic event reached. Again, detailed discussions with residents and stakeholders can provide the modeller with a general feel for the reliability of all anecdotal evidence. Inconsistent facts have to be identified and discarded and discrepancies have to be studied and explained.

4.11.3. Application of Water Level Data in analysis

The principal application of observed water level data in flood projects is in the calibration of hydraulic models and to ensure that the models represent reality.

4.12. Streamflow Data

4.12.1. Introduction to Streamflow Records

Streamflow data is one of the most important data requirements for individual projects and for development of regional procedures. As noted above, streamflow data is calculated from records of water levels, usually collected by major water authorities. The water levels are used to calculate streamflow data by the application of a stage-discharge relationship (rating curve) developed for the station. Continuous records of streamflow can be calculated from the continuous records of water levels. The stage-discharge relationship is often uncertain and application is one of the major sources of uncertainly in the data.

As with water level data, the major water authorities have well established systems for storage and dissemination of their streamflow data. This data is usually available from these agencies, often on line, and almost always free of charge. The data dissemination systems are well organised and data can be supplied accurately and quickly.

Different agencies around Australia maintain appropriate databases of their records. These systems include considerable detail on the type, accuracy and reliability of the gauged data including rating curve accuracy, periods of missing record, number of gaugings and variation in rating curves. In many cases, the system includes photos and maps of the station. This is valuable information and is valuable to ensure that the data is used most effectively. The water agencies are state based and there are differences between the states. Their on-line documentation should be consulted to ensure that the quality and limitations of the record are understood.

There are few other agencies that collect streamflow data, because of the difficulties of calculating the flows from water levels. Where there are other sources of this data, it is usually limited as a part of the research project for a limited duration and locality, and the data is sometimes difficult to obtain. This data is also usually only for a short period of record, but sometimes, it may include an important event. However it is also possible for practitioners to calculate discharge records from water level data using individually developed rating curves that can be prepared from hydraulic models or other theoretical methods.

There are many checks needed when analysing streamflow data. The principal check is on the accuracy and completeness of the stage-discharge relationship. This can be checked by assessment of the number of discharge measurements that have been taken and the maximum discharge (as compared to the maximum recorded water level). As well the variability in the stage-discharge curve indicates that the relationship has changed over time and therefore may be less reliable for particular events. The stage-discharge relationship may be poor for the lower flows because of regular changes in low flow controls. As well it may also be poor at higher flows because of the lack of discharge measurements at higher flows. There are difficulties in extrapolation of the relationships, where there is a change in conditions, for example where the river overtops the banks.

Different gauges in the same catchment can be compared to test for consistency and the water balance and there is a range of other checks that can be carried out. Having more than one gauge in a catchment though is not particularly common.

Poor quality streamflow data may mean poor quality model calibration, so a high standard for checks of data is important. However it is noted that it is very difficult to check the accuracy of the discharge records for a station, and poor quality data may be accepted.

Streamflow records are the basic data source used in developing reliable surface water resources because the records provide data on the availability of streamflow and its variability in time and space. The records, therefore, are used in planning and design of surface water related projects, and are also used in management or operation of projects after construction of the projects is complete.

In addition, streamflow records are used for calibrating catchment modelling systems that, for example, are used for predicting flood behaviour and for predicting hazards arising from design flood events. Records of flood events obtained at gauging stations also serve as one of the basic data sources for design flood estimation, necessary for designing bridges, culverts, dams and flood control reservoirs, floodplain delineation and flood warning systems; and in development of methods applicable to locations where data is not available.

It is essential, to have valid records for a full range of streamflows. The streamflow records referred to above primarily are continuous records of discharge at stream-gauging stations; a gauging station being a site instrumented and operated so that a continuous record of stage and discharge can be obtained. A network of continuous recording gauging stations, however, often is augmented by auxiliary networks of partial record stations to fill a particular need for streamflow data at a relatively low cost. For example, an auxiliary network of sites, instrumented and operated to provide only instantaneous peak level data, is often established.

4.12.2. General Stream Gauging Procedures

4.12.2.1. Introduction

Gauging stations are installed where the need for streamflow records at a site has been recognised. This gauging station will comprise of instruments for measuring the river stage and a location selected to take advantage of the best locally available conditions and discharge measurement and for developing a stable stage-discharge relationship, sometimes referred to as a rating curve. While there are instruments that simultaneously monitor river stage and discharge, the more common instrumentation requires the use of a stage-discharge relationship to convert the monitored river stage into an equivalent river discharge rate. Artificial controls such as low weirs or flumes are constructed at some stations to stabilise the stage-discharge relationships in the low discharge range. These control structures are calibrated by stage and discharge measurements in the field.

Selection of the gauging station site and the development of the stage-discharge relationship are important components in the management of a gauging station and hence the discussion herein will focus on these aspects of management of a gauging station. While there are many other aspects important in management of a gauging station, these two aspects have the most significant impact on prediction of design flood characteristics.

It is rare to find an ideal site for a gauging station and it is more common that the limitations of a site must be considered with respect to the desired data from the site. There are numerous guides on gauging station site selection with the aim of these guides on ensuring the data is reliable and criteria suggested by ISO (2013) are often adopted. When applying data recorded at a stream gauging station, the practitioner must review details of the station carefully and make an assessment of the quality and limitations of the record.

4.12.2.2. Data Collected at a Gauging Station

There are many different approaches to collection of data at a stream gauging station and flood investigations are not necessarily the principal objective of any particular gauging station. As stated previously, the purpose of a gauging station is to collect data about the time history of discharge at that point in the catchment drainage network. In general, the data collected consists of the gauge heights, sometimes referred to as stages. These gauge heights are used as the independent variable in a stage-discharge relationship to estimate the discharge at that point in time. Reliability of the discharge record is dependent on the accuracy and precision of the gauge-height record as well as the accuracy and precision of the stage-discharge relationship.

Gauge-height records may be obtained by systematic observation of a non-recording gauge, or with automatic water level sensors and recorders. Furthermore, various types of transmitting systems are used to relay gauge-height information from remote gauging stations to storage databases.

New technology, especially in the field of electronics and computer based management of field data, has led to a number of innovations in sensing, recording, and transmitting gauge height data. In the past most gauging stations used floats in stilling wells as the primary method of sensing gauge height and these are still in common use today. However, the current trend is toward the use of submersible or non-submersible pressure transducers which do not require a stilling well. Additionally, electronic data recorders and various transmission systems are being used more extensively.

Details of the instruments and associated structures for a stream gauging station are outlined by ISO (2013), Rantz (1982), and World Meteorological Organisation (2010) and hence are not repeated herein. Nonetheless, users of stream discharge data for design flood estimation should ensure that they are conversant with the instruments and structures employed for the collection of streamflow data.

4.12.2.3. Stage-Discharge Relationships

The conversion of a record of gauge-height to a record of discharge is through use of a stage-discharge relationship. The physical element or combination of elements in the stream channel or floodplain that maintains the relation is known as a control. One major classification of controls differentiates between section controls and channel controls. Another classification differentiates between natural and artificial controls. Artificial controls are structures built for the specific purpose of controlling the stage-discharge relation, such as a weir, flume, or small dam. A third classification differentiates between complete, partial and compound controls.

The two attributes of a satisfactory control are stability and sensitivity. If the control is stable the stage-discharge relationship will be stable. If the control is subject to change, the stage-discharge relationship will be subject to change and frequent discharge measurements will be required for the continual re-calibration of the stage-discharge relationship. This increases the operating cost of the gauging station and also increases the uncertainty of streamflow records extracted from the database. Additional data about controls can be found in Herschy (1995).

The traditional way in which a stage discharge relationship is derived for a particular gauging station is the measurement of discharge at convenient times. Traditionally, this measurement is undertaken with a current meter measuring the discharge velocity at enough points over the river cross-section so that the discharge rate can be obtained for that particular stage. By taking such measurements for a number of different stages and corresponding discharges over a period of time, a number of points can be plotted on a stage-discharge diagram, and a curve drawn through those points, giving what is hoped to be a unique relationship between stage and discharge, the stage discharge relationship, as shown in Figure 1.4.4. This rating curve is used in a manner whereby the routinely measured stages are converted to discharges by assuming that the corresponding discharge can be obtained from the curve.

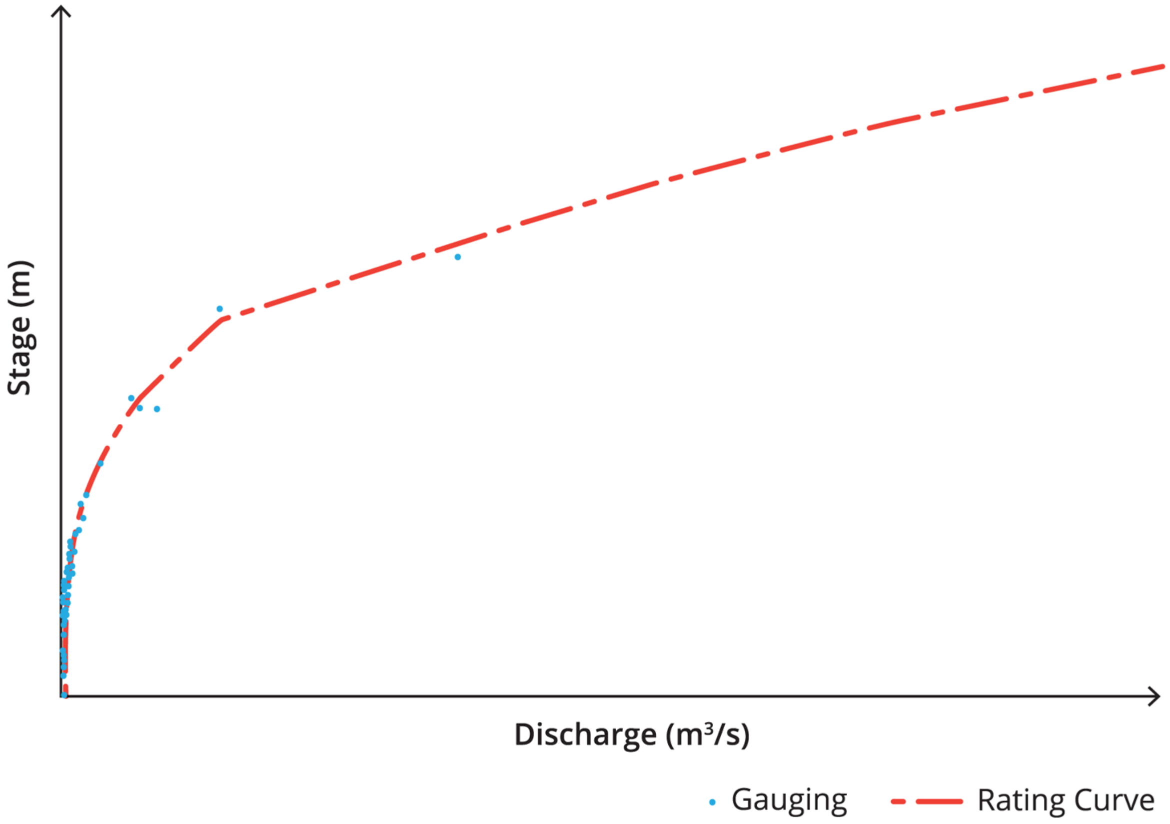


Figure 1.4.4. Typical Rating Curve

There are a number of factors which might cause the rating curve not to give the actual discharge, some of which will vary with time. Fenton (2001) quotes (Boyer, 1964) as describing a list of factors affecting the rating curve, or what he called a *shifting control*. These include:

- The channel and hydraulic control changing as a result of modification due to dredging, bridge construction, or vegetation growth;
- Sediment transport - where the bed is in motion, which can have an effect over a single flood event, because the effective bed roughness can change during the event. As a flood increases, any bed forms present will tend to become larger and increase the effective roughness, so that friction is greater after the flood peak than before, so that the corresponding discharge for a given stage height will be less after the peak. This will also contribute to a flood event showing a looped curve on a stage discharge diagram as shown on Figure 1.4.5. Both Simons and Richardson (1962) and Fenton and Keller (2001) have examined this phenomenon and presented approaches for dealing with this issue;
- Backwater effects - changes in the conditions downstream such as the construction of a dam or flooding in the next waterway downstream;
- Unsteadiness - in general the discharge will change rapidly during a flood, and the slope of the water surface will be different from that for a constant stage, depending on whether the discharge is increasing or decreasing. The effect of this is for the trajectory of a flood event to appear as a loop on a stage-discharge diagram as shown in Figure 1.4.5;
- Variable channel storage - where the stream overflows onto floodplains during high discharges, giving rise to different slopes and to unsteadiness effects; and

- Vegetation - changing the roughness and hence changing the stage-discharge relationship.

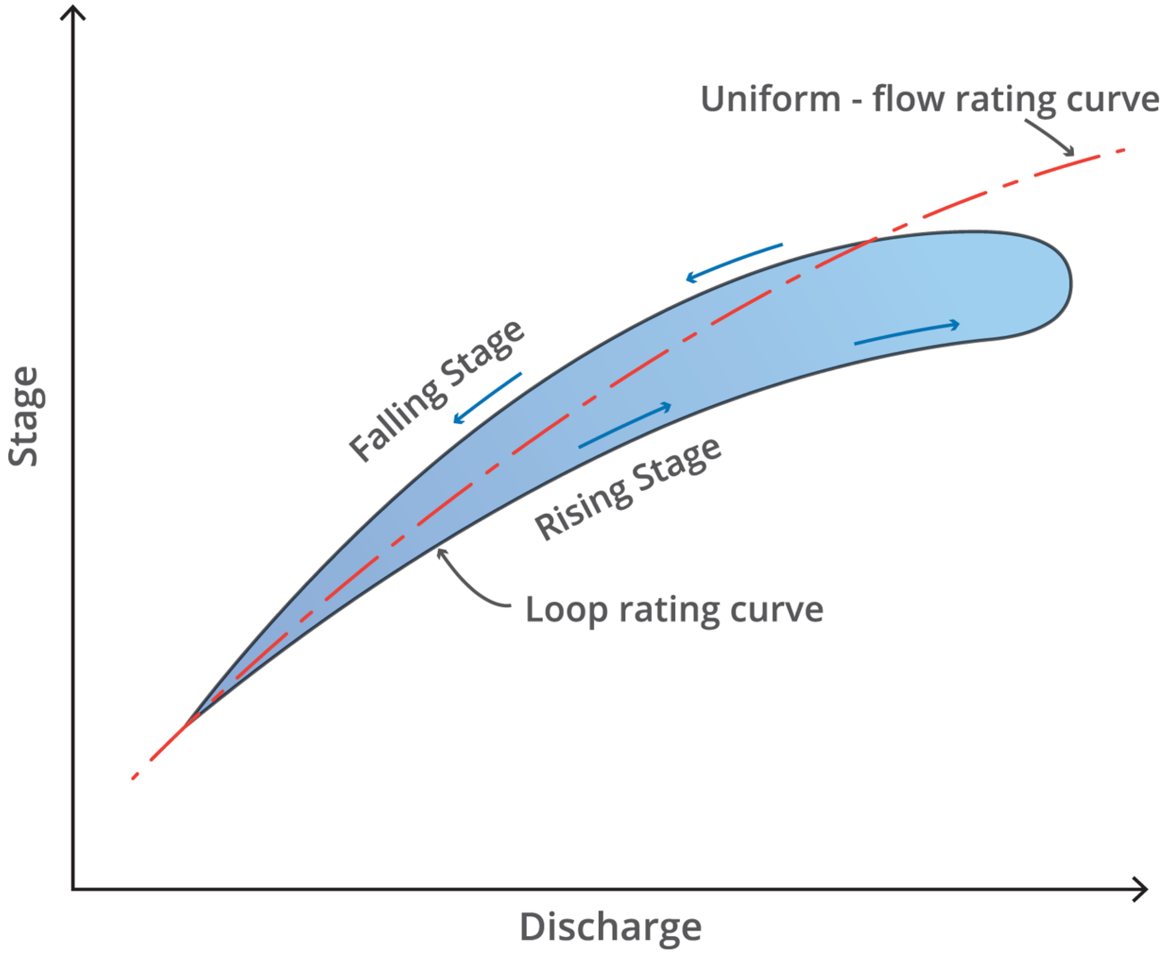


Figure 1.4.5. Loop in Rating Curve

In addition to these generic problems associated with the use of rating curves, there are several problems associated with the use of rating curves for prediction of a design flood characteristic. These include:

- The assumption of a unique relationship between stage and discharge, in general, is not justified;

- Discharge is rarely measured during a flood, and the quality of data at the high discharge end of the curve typically is quite poor because there are usually few velocity measurements at high flow. As a result estimation of the peak discharge of a flood event usually involves extrapolation of the stage-discharge relationship beyond the recorded data points;

- The relationship is usually a line of best fit through the data points defining the stage-discharge relationship. The approach recommended for estimation of this line of best fit in many guidance documents (for example, World Meteorological Organisation (2010)) is a visual fit. This approach provides minimal data on the uncertainty of the relationship and the reliability of any extrapolation of the relationship. This limits the estimation of the propagation of the uncertainty in the flood characteristic prediction approach; and

- It has to describe a range of variation from no discharge through small but typical discharges to very large extreme flood events.

As highlighted in the previous discussion, the unsteadiness of the discharge during a flood event (i.e. the variation of discharge with time) and its influence on a discharge estimate is ignored in the traditional application of a rating curve. In a flood event the slope of the water surface for a given stage will be different from that for the same stage during steady flow conditions; this difference will depend on whether the discharge is increasing or decreasing. As the flood increases, the surface slope in the river is greater than the slope for steady flow at the same stage, and hence, according to conventional hydraulic theory more water is flowing down the river than the rating curve would suggest. The effect of this is shown in Figure 1.4.5. When the water level is falling, the slope and, hence, the discharge inferred is less. The effects might be important - the peak discharge could be significantly underestimated during highly dynamic floods, and also since the maximum discharge and maximum stage do not coincide, the arrival time of the peak discharge could be in error and may influence flood warning predictions. Finally, the use of a discharge hydrograph derived inaccurately by using a single-valued rating relationship may distort estimates for resistance coefficients during calibration of an unsteady flow model.

4.12.2.4. Extrapolation of Stage-Discharge Relationships

The stage-discharge relationship can be considered to consist of two zones. These zones are:

- An interpolation zone where the relationship is within the range of the stage measurements used to develop the relationship; and

- An extrapolation zone where the relationship is not defined by gaugings taken to develop the relationship.

A diagrammatic illustration of these two zones is shown in Figure 1.4.6.

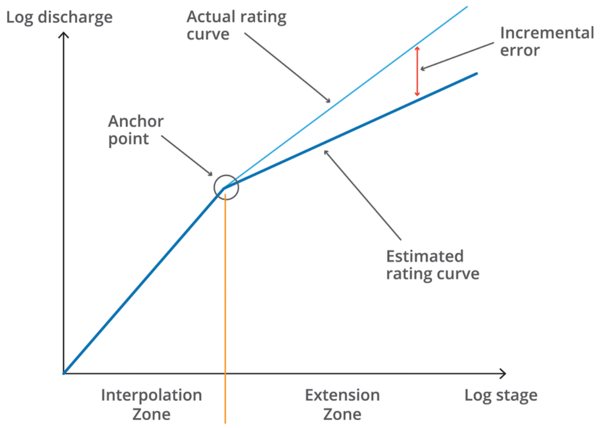


Figure 1.4.6. Stage-Discharge Relationship Zones

While it is preferable that all stage measurements are within the interpolation zone, the nature of the data needed for design flood estimation, and for flood prediction in general, the reliability of data from measurements within the extrapolation zone will require consideration of the extrapolation methodology. The need for extrapolation is shown in Figure 1.4.7 where the discharges for the Annual Maxima Series extracted for the Stream Gauge are plotted as a function of the rating ratio (the rating ratio is the ratio of the recorded discharge to the highest gauging used to develop the stage-discharge relationship). All points in the Annual Maxima Series where the rating ratio is greater than 1 require use of the extrapolation zone of the stage-discharge relationship.

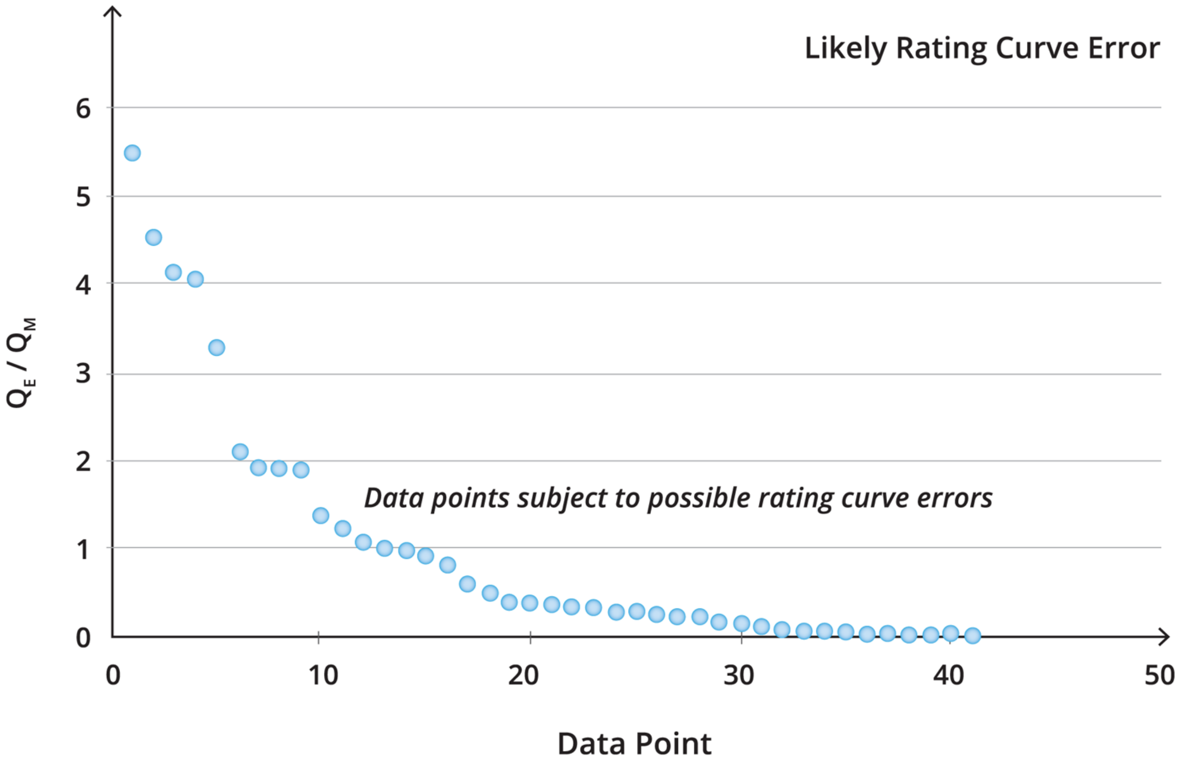


Figure 1.4.7. Annual Maximum Series

As shown in Figure 1.4.7, a number of the values in the Annual Maxima Series are in the extrapolation zone. The accuracy of the values in the extrapolation zone has the potential to influence fitting of the statistical model to the Annual Maxima Series, thereby influencing the predicted design flood quantiles. Fitting a statistical model to data points where the higher values are subject to estimate errors is discussed in Book 3, Chapter 2.

There are a number of alternative techniques for development of the extrapolation zone of the stage-discharge relationship, with a logarithmic extrapolation being often recommended. This approach however may not be applicable because in many cases, the extrapolation may extend from a confined channel into a floodplain.

An alternative approach is the use of a hydraulic model to develop the extrapolation zone of the stage-discharge relationship. Similar to the application of a logarithmic technique, the suitability of this approach needs to be confirmed prior to its application. Of particular concern is the modelling of the energy losses associated with flow in the channel and adjacent floodplains where it is necessary to assume that the parameter values obtained during calibration are suitable for the larger discharges being simulated in the extrapolation zone of the stage-discharge relationship.

The important point in this discussion, however, is a recognition that the values of the data extracted from a discharge record for fitting of a statistical model will contain values where the conversion of the recorded level to an equivalent discharge occurred through extrapolation of the stage-discharge relationship. Consideration of this in the fitting of a statistical model to the Annual Maxima Series is discussed later in Book 3, Chapter 2.

4.12.2.5. Uncertainty of Discharge Measurements

The accuracy, or uncertainty, of a discharge measurement is very important for purposes of assessing the quality and reliability of that measurement. The concept of error and error analysis is a long-standing practice in the field of hydraulics and hydrology. The concept of uncertainty, however, is relatively new. Nonetheless, methods for evaluating, defining and expressing the uncertainty of streamflow measurements have developed.

Uncertainty and accuracy are terms that are sometimes used interchangeably even though they have two very distinct meanings. Accuracy (or error) refers to the agreement, or disagreement, between the measurement of stream discharge and the true or correct value of the discharge at the time of measurement. Since we can never know the true value of the discharge, we can never know the exact amount of error in the discharge measurement.

The uncertainty of a discharge measurement, on the other hand, acknowledges that no measurement is perfect. It is defined, therefore, as a parameter associated with the result of a measurement that characterises the dispersion of values that could reasonably be attributed to the measurement. It is typically expressed as a range of values in which the measurement value is estimated to lie, within a given statistical confidence. It does not attempt to define or rely on a unique true value. To summarise, common usage of the word 'accuracy' for quantitatively describing the characteristics of a discharge measurement is incompatible with its correct meaning. The proper term for expressing the statistical confidence of possible values for a discharge measurement is uncertainty.

The sources of uncertainty in discharge measurements can be categorised as:

- Measurement - these are the uncertainties associated with taking the measurements. The primary component in this category is instrument accuracy. The accuracy of both the velocity meter and the level recorder need to be considered.
- Methodology - these are the uncertainties associated with the analysis of the recorded measurements to enable the development of a point on the stage-discharge relationship. In this category, features such as the assumption of linear variation in the cross-section between the bathymetric points, the assumption of a logarithmic vertical velocity profile, wind effects, changing stage during measurement, etc need to be considered.

World Meteorological Organisation (2010) guidance on the likely standard errors encountered in undertaking a gauging point are:

- For rod suspension, the standard error ranges from 2% for an even, firm, smooth and stable streambed, to 10% for a mobile, shifting sand, or dunes streambed;
- For cable suspension, the standard error ranges from 2% to 15% for an unstable streambed, high velocity, and vertical angles; and
- For acoustic depth measurements, the standard error ranges from 2% for a stable streambed to 10% for a mobile, shifting sand, and dunes streambed.

4.13. Catchment Data

4.13.1. General

Catchment data is an essential component for estimation of design flood characteristics and there are various types of catchment data required. Furthermore, data is available from different sources and with a range of accuracies. Generally, it is advisable that practitioners seek the most suitable data in each instance and assess the required accuracy of that data in respect of the desired accuracy of the outputs.

4.13.2. Types of Catchment Data

There are many alternative types and forms of catchment data relevant to estimation of design flood characteristics, one of the major forms being those associated with assessment of flood behaviour. To predict this flood behaviour, the following types of data may be required:

- Topographic and infrastructure data including structures within the floodplain including culverts, bridges, and pipe networks;
- Land use information;
- Vegetation data; and
- Soil data.

4.13.3. Topographic and Infrastructure Data

4.13.3.1. General

Topographic data is an important component of any design flood investigation. Proper scoping of topographic and infrastructure data collection can have a significant impact on the cost effective delivery of flood investigations. The scope of the required topographic and infrastructure data is driven by the nature of flood behaviour for a given area. The desired elements of topographic and infrastructure data include:

- Catchment extent;
- Catchment slope;
- Drainage topology (i.e. the drainage flow paths and network of channels);
- Channel cross-sections;
- Waterway structures (weirs, levees, regulators, dams, culverts and bridges etc);
- Overland flowpath definition; and
- Infrastructure (bridges, culverts, pits, pipes etc).

There are a number of alternative approaches to obtaining the necessary topographic data including:

- Field survey;
- Airborne techniques; and
- Available spatial mapping.

4.13.3.2. Field Survey

Discussed in this section are details of the scoping of the field survey component for an investigation for design flood estimation. The focus is on those features where field survey is needed to capture the desired information. These features include:

- Channel and overland flow path cross-sections (and potentially long-sections);
- Waterway Structures - weirs and regulators;
- Infrastructure - bridges, pipes, pits and culverts;
- Road and rail embankments;
- Levees; and
- Property data (floor level, type of building, size, location).

While it is possible to obtain existing field survey data from other sources, it is important to assess its suitability for the intended purpose. In other words, it is necessary to obtain both the data and the meta-data, which includes items related to date of capture, accuracy, etc.

4.13.3.2.1. Cross-Sections

A survey of cross-sections is required only when the design flood estimation requires application of a catchment modelling system to generate data that is not available from a catchment monitoring program. Hence, the scope of a cross-section survey depends on the type of the catchment modelling being used. Where catchment modelling is focussed on hydrologic simulation (using, for example, a conceptual rainfall-runoff model), the cross-section data required is minimal. However, where the catchment modelling requires hydraulic simulation (using, for example, a one dimensional network model), the cross-section data required will be more extensive.

The important characteristics of the cross-section data include the lateral extent and longitudinal spacing of cross-sections. The lateral extent of the cross-section must be sufficient to include key in-bank elements and extend to above the highest flood level, which often extends onto the floodplain and outside the stream channel. When surveying in-bank cross-sections, good field notes and/or photos describing the nature of the channel are vital for proper interpretation post collection. There are numerous references such as Stewardson and Howes (2002) that describe flood study cross-section survey requirements in detail. The overriding principle being that the cross-section data is adequate to estimate the shape and slope of the channel so that suitable estimates of the flow conveyance capacity of the channel can be calculated.

The influence of in-bank features on flood discharge behaviour tends to reduce as the magnitude of the flood discharges increases. For example, bank-full capacity of a river channel may represent 100% of a 0.2 or 0.5 EY discharge but less than 10% of a 1% AEP discharge.

4.13.3.2.2. Structures and Drainage Infrastructure

Structures in the waterway and on the floodplain may have a significant influence on flood behaviour. Structures requiring survey include:

- Levees;
- Road and rail embankments;
- Hydraulic structures such as weirs, bridges and culverts;
- Fences; and
- Drainage infrastructure such as pipes and pits.

Often these structures constrict and obstruct flood discharges thereby influencing the design flood estimation. The effects on flood behaviour may be intentional (such as a weir) or unintentional (such as blockage at a culvert). Where the effect on flood discharge is unintentional, it is worth noting that the effect may be stochastic and hence the likelihood of the effect needs to be considered by a suitable joint probability technique. Irrespective of whether the influence is intentional or unintentional, these structures will have an influence on the estimation of the design flood characteristic.

Hydraulic structures generally act to control the discharge behaviour in accordance with a particular management strategy. As most management strategies are concerned with frequent discharges, there are control structures designed to operate under flood conditions as part of an operational flood management strategy. Hence, the impact of these structures will vary with the management strategy and flood magnitude.

The purpose of a levee is to divert discharges as part of an operational flood management strategy. As part of this strategy, levees are designed only to protect floodplains for a specified portion of the relationship between the likelihood and magnitude of a flood event; in other words, there is a defined probability that a levee can be overtopped (with or without failure of the levee bank) by a flood rarer than the levee was designed to protect against. Hence, in design flood estimation, the geometric properties of a levee are important to enable suitable estimation of the flood magnitudes (and hence probabilities) of design events likely to result in hydrologic (and/or structural) failure of the levee.

Similar to field survey of cross-sections, field practicalities such as vegetation, access and water depth and flowrate may influence the location and details surveyed for a given structure.

4.13.3.2.3. Field Survey Techniques

The techniques used for collection of field survey data (typically by surveyors) are discussed in this section. Details of three techniques are presented; namely Traditional Ground Survey, Real Time Kinematic (RTK) Global Positioning Systems (GPS)/ Differential GPS, and Photogrammetry. Typical accuracies for each of these techniques are provided in Table 1.4.1. The techniques to measure topography and other survey features generally fall into two main categories:

- Direct measurement - where the survey technique involves a ground based instrument measuring features by physical contact and relating the measurement directly related to know ground control such as a State Survey Mark (SSM); or
- Remote sensing - where features are measured without physical contact with the object, and generally refers to measurement by an airborne or satellite mounted instrument.

Table 1.4.1. Typical Accuracies of Field Survey

Survey Technique	Nominal Accuracy (+/- m)	
	Vertical	Horizontal
Traditional Ground Survey	0.01	0.01
RTK GPS	0.05	0.05
Photogrammetry	0.1-0.3	0.2-0.5
ALS (LiDAR)	0.15-0.4	0.2-0.5

4.13.3.2.3.1. Traditional Ground Survey

Traditional ground survey (that is, survey collected by traditional or total station ground survey techniques) is the most accurate survey technique with vertical and horizontal accuracies as shown in Table 1.4.1. However, this technique is manual and labour intensive and is therefore best suited to small and/or difficult areas for other techniques, to supplement data obtained from other techniques, and to validate data obtained from other techniques.

In the context of a design flood estimation, traditional ground survey methods are often used for:

- Checking remote sensed data sets; and/or
- Supplementing remote sensed data in:
  - Areas that are impenetrable from the air (for example, satellites and aeroplanes have difficulty in sensing the ground in areas like the bank of channels and/or heavily vegetated areas);
  - Areas that are critical for the data being sought from the catchment modelling system (for example, critical hydraulic controls such as levees and weirs) where topographic accuracy is important.

4.13.3.3. Real Time Kinematic Global Positioning Systems and Differential Global Positioning Systems

Real Time Kinematic Global Positioning Systems (RTK GPS) involves coordinated use and comparison of two Global Positioning Systems (GPS) using the same satellite signals. The first GPS, sometimes referred to as the 'base station', is positioned over a known location (typically a permanent survey mark) and maintains a continuous record of the location relative to numerous satellite positions. The second GPS, referred to as a 'roving GPS', can be hand-held or mounted to a car, boat or an all-terrain vehicle; this unit collects data defining the location of the roving GPS position from the same satellites. The accuracy of the roving GPS location is enhanced by comparison of the satellite signals for the two stations. Shown in Figure 1.4.8 is the concept underpinning field survey using RTK GPS techniques.

RTK GPS has the advantage that it can collect a reasonable amount of data at higher accuracy than remote sensed data and much faster than by traditional means. The disadvantage is that if the vehicle in which the RTK GPS is mounted is unable to access an area, the system may have to be dismantled to gain access by some other means or measurement of data is not possible in the inaccessible area. RTK GPS methods also rely on the instrument having line of sight access to an array of satellites. This can be a limitation to the technique in areas underneath a tree canopy.

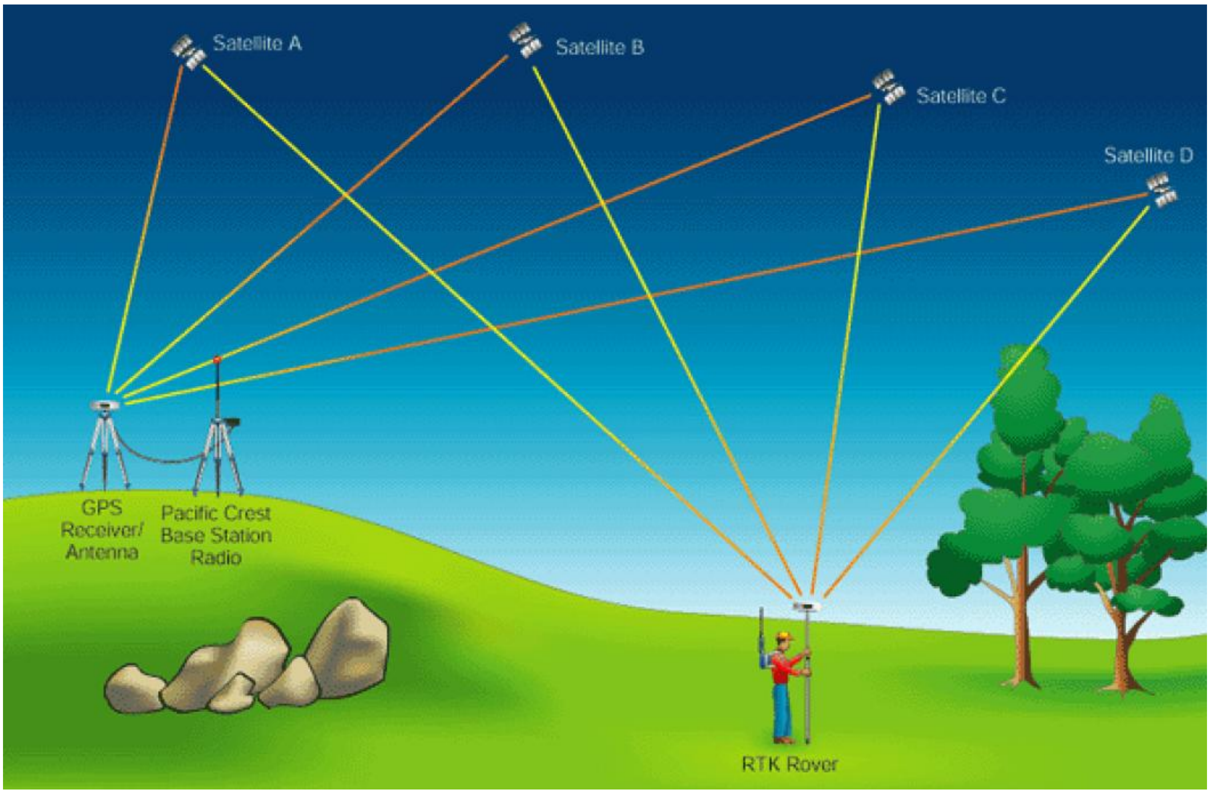


Figure 1.4.8. Concept of RTK GPS Technique of Field Survey

4.13.3.4. Airborne Techniques

Defining flood behaviour within an area containing overland flowpaths requires extensive topographic data. Aerial techniques are well suited to capture this topographic data across a broad area. Commonly, this topographic data is represented as a Digital Elevation Model (DEM). It should be noted that there is no universal definition of the terms Digital Elevation Model (DEM), Digital Terrain Model (DTM) and Digital Surface Model (DSM) in scientific literature. In most cases, the term DSM represents the earth's surface and includes all objects on it. In contrast to a DSM, the DTM represents the bare ground surface without any objects like plants and buildings. Both DTM and DSM may be referred to as DEM.

Usually, a DEM is represented as a raster (a grid of squares) or a vector-based Triangular Irregular Network (TIN). According to Toppe (1987), the TIN DEM data set is referred to as a primary (measured) DEM, whereas the Raster DEM is referred to as a secondary (computed) DEM; this definition, however, predates the widespread availability of Airborne Laser Scanning (ALS) (also known as Light Detection and Ranging - LiDAR) data for definition of the catchment surface topography.

Before embarking on any aerial data capture, it is worth liaising with other agencies that may hold topographic data to ensure that the existing spatial extent of data does not cover the desired area.

At present, the two principal techniques used in aerial survey for obtaining topographic data are:

- Photogrammetry; and
- Airborne Laser Scanning.

A general description of photogrammetry is that it is the science of making measurements from photographs; in the context being used herein, it is the science of making measurements about the topographic surface of catchments. Generally, topographic data obtained through photogrammetry consists of spot elevations plus linear breaklines and the topographic surface is then determined from the TIN model through spot elevations. The breaklines are lines in the TIN that represents distinct interruptions in a surface slope, such as a ridge, road, or stream. No triangle in a TIN may cross a breakline (in other words, breaklines are enforced as triangle edges). Elevation levels along a breakline can be constant or variable.

ALS or LiDAR is a remote sensing technology that measures distance by illuminating a target (in this case, the ground surface) with a laser and analysing the reflected light. Raw ALS data consists of a dense cloud of spot elevations classified into ground and non-ground strikes. This raw ALS data usually has the non-ground strikes removed prior to provision. Analysis of the raw ALS data usually will result in a raster DEM.

It should be noted that neither photogrammetry nor ALS can penetrate water surfaces. Only the water surface level at the time of capture can be measured. If the bathymetry under the water surface is relevant in the context of the numerical modelling, bathymetric data must be collected and incorporated separately. Similarly, neither of the two methods can penetrate dense vegetation (such as trees, sugar cane and mangroves) to produce ground elevations. Hence, ground survey may be necessary to fill gaps in the topographic data under heavy vegetation.

It is important in a DEM to ensure key linear features such as levees, embankments and other infrastructure are adequately represented. These features can be incorporated into the topographic description using field data as breaklines.

The ANZLIC Committee on Surveying and Mapping have developed guidelines on the acquisition of LiDAR (ANZLIC, 2008) in terms of accuracy, data formats and meta-data. They have also developed the National Elevation Data Framework.

Further discussion of these two aerial survey techniques is provided in the following sections.

4.13.3.4.1. Photogrammetry

Photogrammetry is a measurement technique where the three dimensional (x,y,z) coordinates of an object are determined by measurements made from a stereo image consisting of two (or more) photographs; usually, these photographs are taken from different passes of an aerial photography flight. In this technique, the common points are identified on each image. A line of sight (or ray) can be built from the camera location to the point on the object. It is the intersection of its rays (triangulation) that determines the relative 3D position of the point as the known control points can be used to give these relative positions absolute values. More sophisticated algorithms can exploit other information on the scene known as priori.

The accuracy of the photogrammetric data is a function of flying height, scale of the photography and the number and density of control points. Typically, the accuracy requested when scoping photogrammetric data collection for flood study purposes ranges from +/- 0.1 m to +/- 0.3 m. Note that the accuracy of the developed design flood profile cannot have an accuracy better than the catchment data used to estimate the design flood profile.

As the technique is based upon the comparison of photographic images, shading and obscuring of the ground surface by vegetation can reduce coverage in specific areas.

However, as photogrammetric analysis can utilise manual inspection of the stereo pair of photographs, the photogrammetrist is sometimes able to pick the odd ground surface visible through tree or crop cover. In this way, photogrammetry is sometimes able to provide some reliable points in vegetated areas.

Shown in Figure 1.4.9 is a region over which photogrammetric data coverage and ALS data coverage will be demonstrated. Shown in Figure 1.4.10 is a typical sample of the raw data obtained from a photogrammetric technique while shown in Figure 1.4.11 is the raw data in finer detail for the area indicated in Figure 1.4.10. These figures demonstrate the following specifically in relation to photogrammetry:

- The measured points are well spaced, but not always on a grid. Some manual manipulation has occurred in locating these points when necessary.
- Breaklines (seen as intervals along which measured elevations form the vertices of the interval) are evident along tops and bottom of banks. These are most likely to have been manually derived by viewing the stereo pair of photographs.

Figure 1.4.9. Aerial Photograph Example (Region A)

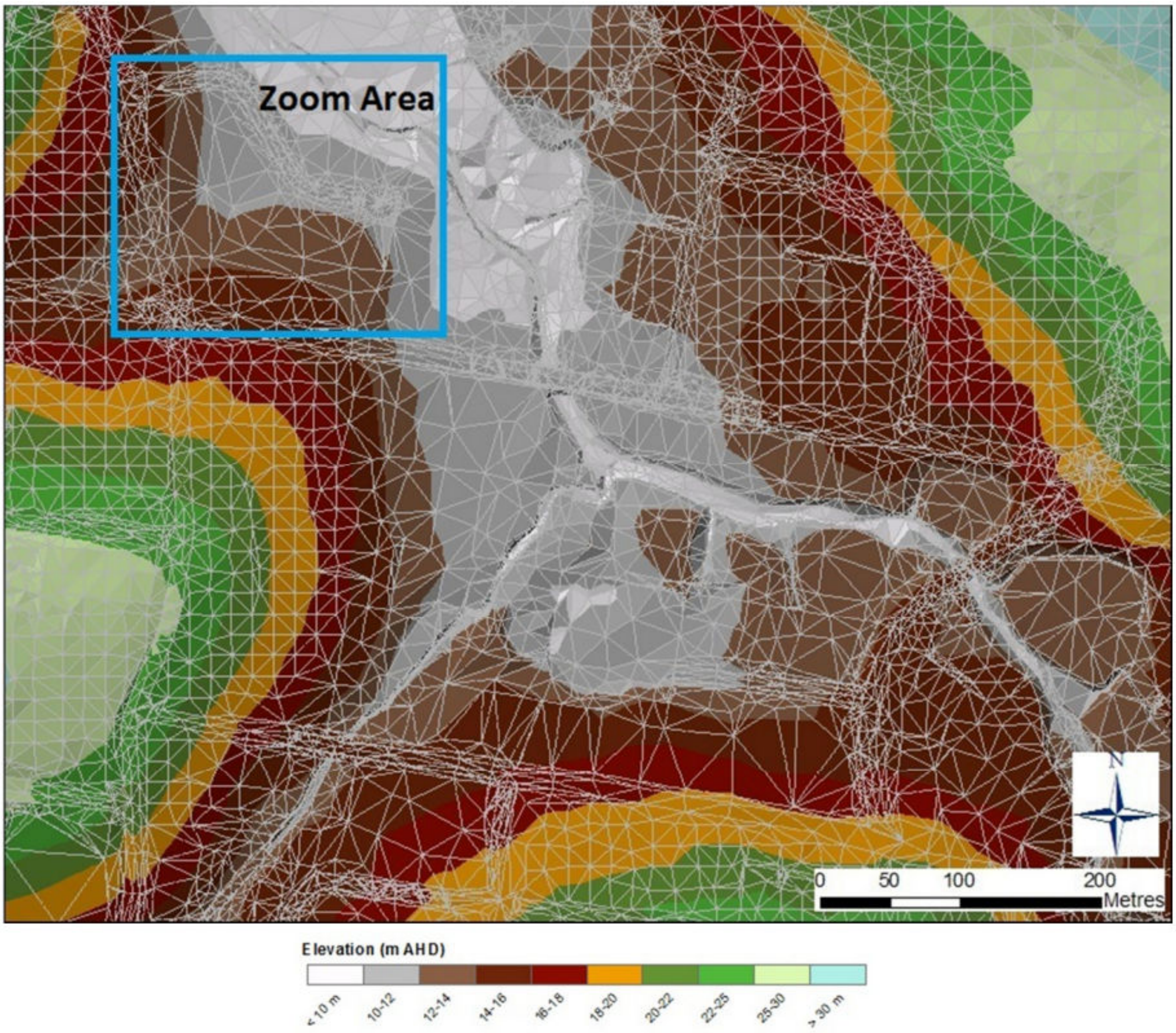


Figure 1.4.10. Sample of Processed Photogrammetry data set (Region A)

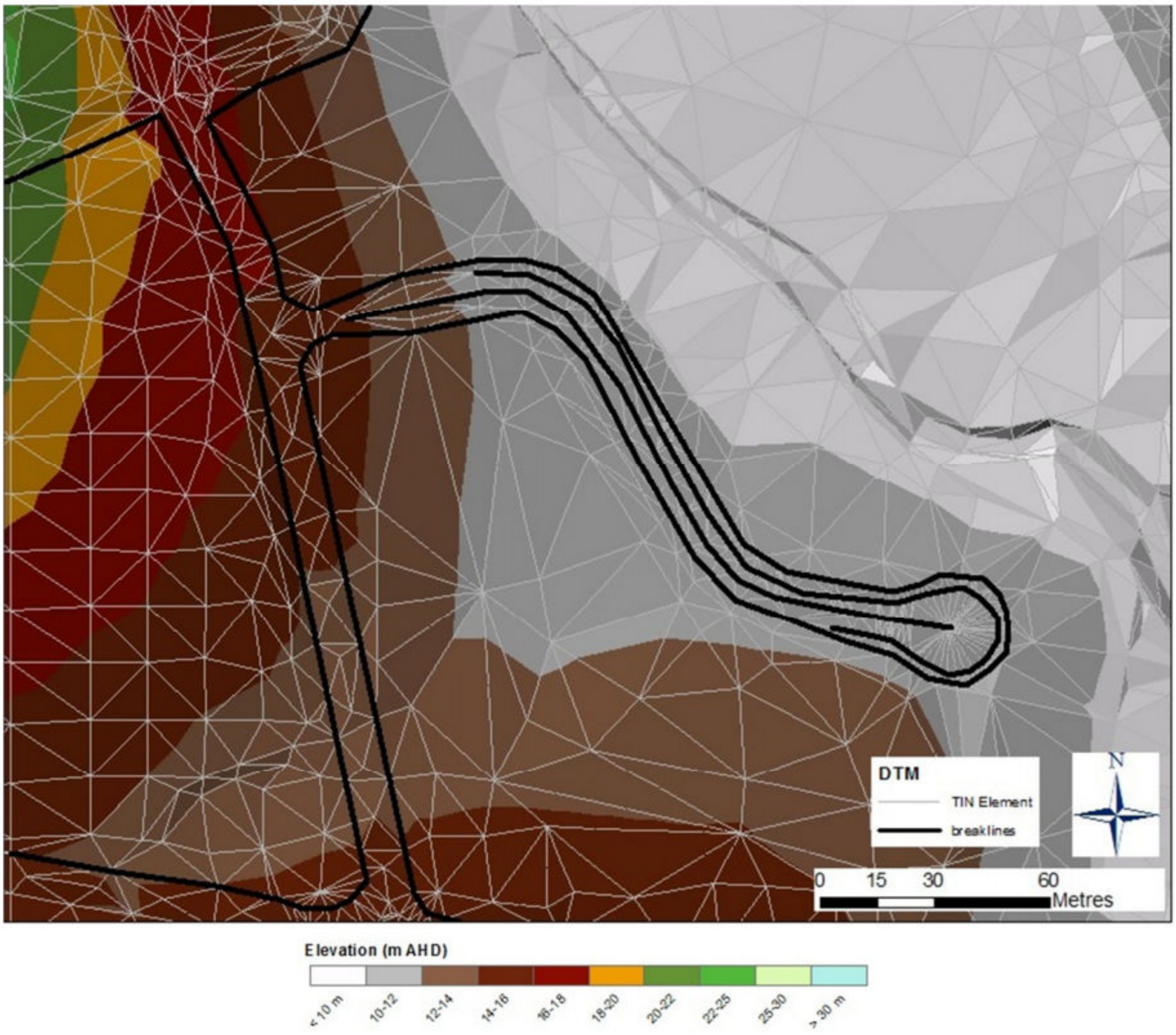


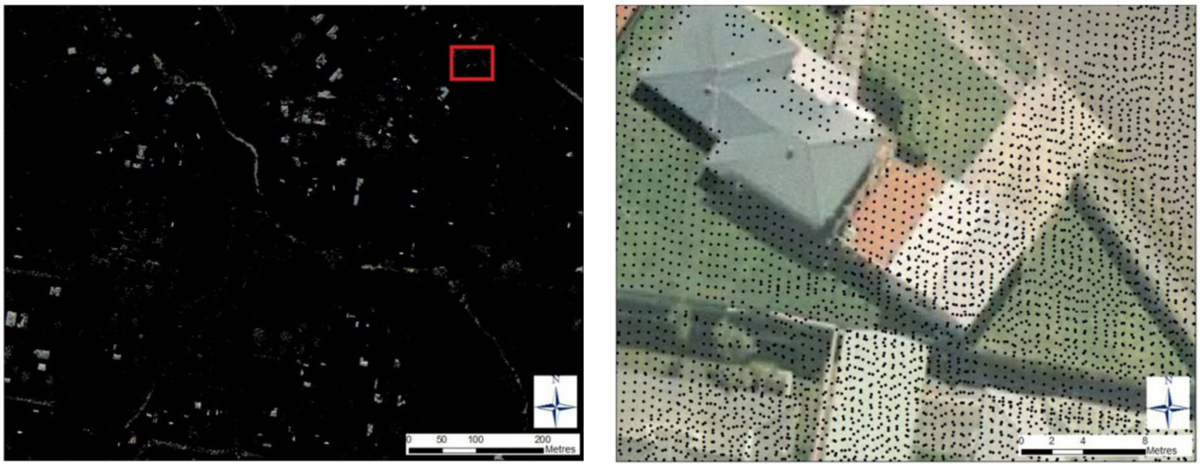
Figure 1.4.11. Sample of Processed Photogrammetry data set (Region A detail)

Photogrammetry is also often used to develop contours of the land surface directly as polylines with an attributed elevation; these contours are then used to create the desired elevation data set.

4.13.3.4.2. Airborne Laser Scanning

ALS or LiDAR consists of a high frequency laser emitter and scanner, coupled with a GPS and an Inertial Measurement Unit (IMU), all mounted in fixed winged aircraft. Rapid pulses of light are fired toward the earth by the laser instrument. These light pulses rebound from a target and are sensed. The scanner records the time differential between the emission of the laser pulses and the reception of the return signal. The time taken is used to determine the distance between the emitter and the target. The position and orientation of the scanner is determined using differential kinematic GPS and the IMU to account for aircraft pitch.

ALS produces a dense cloud of points (See Figure 1.4.12). These points can be classified as ground or non-ground points. While ALS requires little ground control in acquisition, ground control is important for quality control of the ALS measurements. For example, while it may be easy to scan inaccessible or sensitive areas without ground survey, the accuracy and reliability of the collected data may be low; in other words, ground control is important for ensuring the accuracy and reliability of the ALS measurements.



(a)

(b) Zoom area indicated by red square in (a)

Figure 1.4.12. Sample of Raw ALS data set (Region A)

The vertical and horizontal accuracy of ground surface level measurement by ALS is a function of the laser specification, flying height, ground control and the surface coverage. Hard road surfaces, for example, normally are able to be measured accurately, but other surface types (for example, swamps or heavily vegetated areas) are not easy to measure and hence the measurements must be treated with caution. It is useful to note that many quoted accuracy values for ALS data are in reference to the data accuracy for clear hard ground. For clear, hard ground (that is ground with no surface coverage), the nominal accuracy for technology commonly applied in Australia is:

- Horizontal accuracy:
  - 1/3000 x altitude at which the aeroplane is flown; for a flying height of 1000 m, the horizontal accuracy is about +/-0.33 m; and
- Elevation accuracy:
  - < +/-0.15 m @ 1100 m flying height
  - < +/-0.25 m @ 2000 m flying height
  - < +/-0.4 m @ 3000 m flying height

The width of the land terrain sampling per pass, commonly referred to as the swath varies with the flying height. While typical values are given in Table 1.4.2, users are advised to obtain the meta-data regarding their ALS to ensure suitability for purpose.

Table 1.4.2. Typical Swath Values

Typical Swath (m)	Altitude (m)
800	1100
1456	2000
2184	3000

A disadvantage of the ALS data capture method (compared to, for example, low-level photogrammetry) is the absence of breaklines in the data to define distinct, continuous topographic features and significant changes in grade. While the horizontal density of points usually is quite high (average point spacing of 1 to 2 metres depending on flying height and sampling frequency), features such as narrow banks/levees or channels will only be resolved if the data are sampled on a very small grid (less than 1 to 2 m grid). This can result in large and unwieldy terrain files.

There are a number of approaches that can be taken in relation to the treatment of breaklines in ALS data sets:

1. Sample the entire survey area at a fine resolution - say on a regularly spaced 1 m Digital Elevation Model (DEM) grid and manually identify important salient topographic features and hand enter these features into the models;

2. Use local knowledge, GIS, aerial photos, satellite imagery or historic plans to identify locations of important features and hand-digitise over the fine resolution DEM in a manner similar to the first approach (approach 1) and then drape values from the DEM to develop 3D breakline strings;

3. Use observations as in approach 2 to determine locations of key features and then use field survey to develop 3D breakline strings; and

4. Use auto-processing/filtering algorithms to extract breaklines from the raw ALS data.

Experienced users favour a combination of technique approaches (2), (3) and (4). While approach (4) nominally provides the widest coverage and extracts the most information from the ALS data, the processes cannot be considered reliable as no method has been developed for testing the validity of the breaklines produced.

Although requiring a greater manual input, it is considered that approaches (2) and (3) are better approaches for the provision of reliable estimates of the surface level at critical locations with in the floodplain. This arises from the manual checking that occurs during the progress of approaches (2) and (3). Furthermore, long-sections from the ALS can be checked for consistency and a sub-sample tested against field measurements as a validation process.

Capturing ALS data results in surface level estimates from various ground coverages including bare earth, vegetation, and buildings. Thorough processing of this raw data is required to ensure a true representation of the ground surface is obtained.

Raw ALS data files contain all returns can be very large leading to difficulties with data storage and the manipulation of this data. As a result, a common approach is to use 'thinned' ALS data; this is data that has been processed to remove data points providing limited additional definition of the terrain surface. Shown in Figure 1.4.13 is an example of the processed ALS data set to produce the thinned ALS data set. Illustrated in this figure are the following aspects:

- The measured spot heights are provided as a grid; in other words, each spot height is representative of an area defined by the grid dimensions. This grid has been created by "thinning" the raw ALS point cloud data set. While the dimensions of the grid are defined by the user, it is useful to note that the smaller the grid, the larger and perhaps more unwieldy the data set being used but the surface topography will have an apparent higher definition. Conversely, the larger the grid, the smaller the data set but the surface topography will have an apparent lower definition. It is also worth noting that definition of the surface topography only needs to be adequate to provide the necessary information and that any additional definition will not provide either additional flood data or accuracy of the predicted flood data.

- There are no breaklines in the model of the surface topography. Breaklines can be created according to the approaches discussed previously but typically are not determined solely from the ALS data.

- Areas where there are no measurements and hence no points available to build the model of the surface topography. In these areas, the ground surface was not visible due to, for example, heavy vegetation or surface water. These areas can be removed during the processing as "non-ground" points. When using a processed ALS data set, there will be situations where a non-ground elevation point (for example, a point that has hit the canopy of trees) has not been removed during processing. As a result, the spot elevation remains in the data set and would be treated as a surface elevation. In some situations. Errors of this type are obvious and can be removed manually. In other situations, they may not be obvious and hence will form part of the DEM (Digital Elevation Model) used in the analysis. Users need to be cognisant of errors of this type in ALS data and the consequent significant impacts on the predictions obtained from the catchment modelling system.

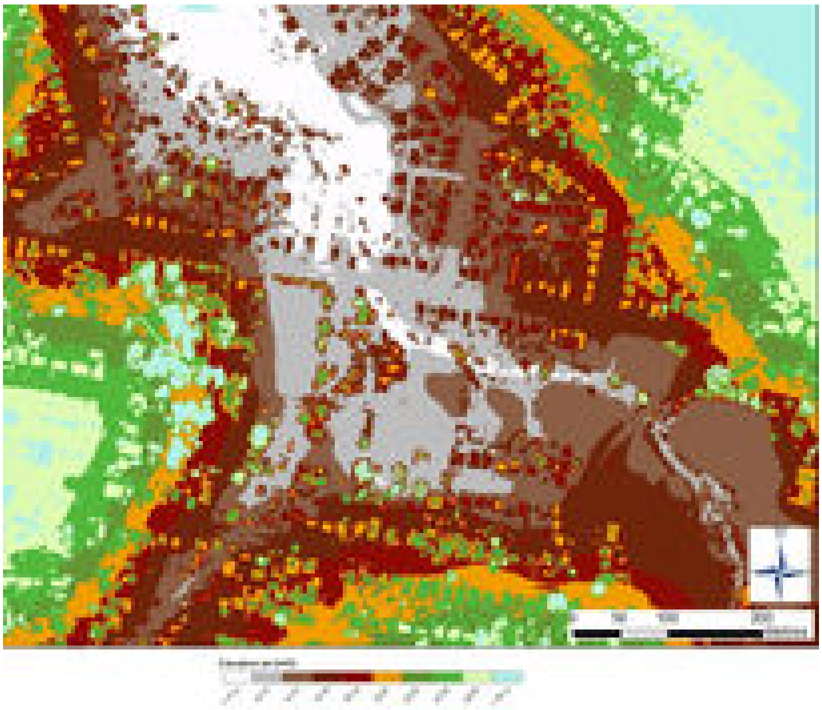


Figure 1.4.13. Sample of Processed ALS data set (Region A)

4.13.3.4.3. Aerial Survey Quality Checks

As discussed in Book 1, Chapter 4, Section 13, survey data is not exact and will have a tolerance or a stated level of accuracy. Data obtained from aerial survey is the same. With data obtained from aerial survey, accuracy is dependent upon a number of factors, including flying height and the number of control points. In general, the required accuracy is advised prior to commencement of data collection and the surveyor designs the data collection program needed to achieve the desired accuracy.

An important point to note is that the accuracy of the collected data is checked and confirmed. The resultant stated accuracy typically does not apply to the DTM derived from the survey data but rather to the individual elevation points sampled during the data generation program. This is an important distinction and users of a DTM derived from aerial survey data needs to be aware of this feature.

There are a number of methods that may be used to check the accuracy of the aerial survey.

1. POINT v DTM SURFACE: Independent field surveys of selected quality check points can be compared to the DTM. However, this surface has been interpolated from the aerial elevation data and, unless the accuracy stated by the aerial surveyor referred to the DEM, the correlation in accuracy values is not guaranteed. But, this method can provide a preliminary indication of accuracy, particularly if the independent field survey points with known accuracy are already available from another source;

2. POINT v POINT: Independent field surveys of selected quality check points can be compared to the individual aerial data elevation points. The selected check points must exactly match the coordinates of the aerial data points to ensure that a valid comparison is being made. To do this, the aerial survey must first be received in order to select the points at which comparison will be made, which may slow the data collection phase. Alternatively, early liaison with the aerial surveyor may allow the location of a number of points to be known before data provision, which may save time; and

3. STRING v DTM SURFACE: A more appropriate approach may be to field survey a number of breakline strings along key linear features. These strings may be some 50 m - 200 m in length with points at regular spacing (say every 5 -15 m). A comparison can then be made of the profiles along the feature determined from both the aerial and field survey. In addition, if the strings are across conveyance paths (i.e. they are cross-sections), the modeller can check that conveyance cross-sectional areas are adequately represented. These comparisons enable a qualitative assessment of aerial survey accuracy for a given region within the study area. A number of surveyed strings may be required across the study area to gain an overall appreciation of accuracy.

4.13.3.5. National Digital Elevation Model

National grids of terrain information are available from Geoscience Australia. These data sets use information obtained from a variety of sources inclusive of satellites. As a result, these data sets tend to be coarse with grid sizes varying from 1 second (1 seconds in longitude and latitude is approximately 30 m) to 9 seconds (9 seconds in longitude and latitude is approximately 250 metres). As development of these databases occur, it is likely that these specifications will change. Therefore, as with other sources of data, users should ensure that they use the most appropriate data for their problem.

4.13.3.6. Bathymetric (Underwater) Techniques

Many methods for generating surface data are not applicable for collecting bathymetric data (ground data below the water surface) in permanent or semi-permanent water bodies. Where a water body has not been surveyed adequately, a specific survey will be required to supplement the ground surface data.

If the water body is shallow or small, then a traditional surface survey technique may be suitable. For deeper, larger water bodies, a specialised bathymetric survey may be required. Instruments such as echo sounders, side scan sonar systems and acoustic doppler profilers may be used for this purpose.

In most cases, the bathymetric survey will need to be merged with ground surface data.

While bathymetric surveys have been conducted for most major rivers, if the data is not recent and the riverbed is subject to change then the data should be checked for suitability prior to its use.

4.13.3.7. Aerial Photographs

Aerial photographs are an important source of qualitative data and can be collected during an aerial survey. Geo-referenced (or ortho-rectified) aerial photos can be supplied as part of a photogrammetric survey. These geo-referenced aerial photographs are aerial photos where spatial coordinates have been added to locate the photograph. It is important to recognise that the raw aerial photograph is spatially distorted, being a planar image of a curved surface of variable height. In ortho-rectifying the image, the image is scaled, rotated and stretched so that various reference locations move to their correct coordinate locations.

A consequence of this is the location of features on an aerial photograph will have a degree of uncertainty. For example, if a rectified aerial photograph is used to locate a flood mark, the attributed location will be subject to a tolerance. In an area of high flood gradient this can result in differences between observed and simulated flood levels that do not accurately represent the true differences.

Aerial photographs, while not providing quantitative data directly, can provide additional information about flowpaths, flow obstacles and floodplain vegetation that is not always immediately evident or accessible on a site inspection. Additionally, aerial photos can be a useful guide when defining parameters for floodplain characteristics (for example, roughness coefficients) and can be used to develop a spatial map of the floodplain parameter.

Another example of the use of aerial photography is its use in urban areas to define building outlines or fence lines where these are to be included within the hydraulic model and can be a reasonable source of information for assessing the total imperviousness of a catchment (see Book 5, Chapter 4).

Finally, when historical aerial photography is available, it is useful in assessing catchment development or sourcing information on the floodplain development when historical events occurred.

4.13.3.8. Historical Topography and Infrastructure

All data collection methods covered thus far have been concerned with present day catchment conditions. However, when catchment modelling systems are used for design flood estimation, calibration to historical events is required and the catchment and floodplain conditions at the time of the historical event need to be considered particularly as these conditions may not be the same as present day conditions. In addition, if a number of events are to be used during the calibration process, changes to catchment conditions may occur between events.

Conditions at each of the relevant historical points in time must be established and used in the model development; this is discussed in more detail in Book 7. Changes to conditions that may affect flood behaviour include dam construction, initial dam storage levels, dredging or siltation of river channels and particularly of river mouths, construction of levees and other associated flood mitigation works, road construction including the raising or duplication of roads, the realignment of road embankments, the construction of new culverts and/or bridges, upgraded drainage networks both in rural and urban environments, developments on the floodplain, the construction of new weirs or the removal of old weirs, different crop types or stage in the growing season, and others that have not been mentioned here. Depending upon the length of time since the occurrence of the calibration event, record of these changes may be only available anecdotally.

The availability of data for historical events needs to be considered when the event is used as part of the design flood estimation. For example, there may be anecdotal or even good formal measurement evidence of a record flood that occurred 100 years ago but details of this flood event may not be adequate for its use as a calibration event for validation of a catchment modelling system. On the other hand, the data may be adequate for it to be included as a high discharge censored event in a flood frequency analysis (Book 3, Chapter 2).

4.13.3.9. Land Use Information

Land use data is important for several aspects of projects, and can be obtained from land use maps, field observations or consultation with local authorities, land managers or property owners. Local authorities are often a valuable source of land use data.

Land use data is used in hydrology models to determine suitable parameters to calculate runoff and is also used in hydraulic models to assist in the determination of Manning's n values.

Land use data is normally supplied as a map or a GIS layer. When obtained from local authorities, the data is usually supplied on request for no charge.

Information on land use can be used in the hydrologic model to determine percentage impervious or in hydraulic models to inform hydraulic roughness. Land use information may be sourced from:

- Local or State Government Authorities in spatial layers of existing development zonings;
- Local or State Government Authorities in spatial layers of future development zonings; and
- Inferred from Aerial photographs (current and historical).

4.13.3.10. Vegetation Data

Information on vegetation type can be used in the hydrologic model to determine runoff characteristics or in hydraulic models to inform hydraulic roughness values (Manning's n). This data may be sourced from:

- Vegetation maps;
- Field inspections; and
- Inferred from Aerial photographs.

Care needs to be taken with vegetation maps as, in general, the maps are based on limited sampling and inferring the results of this survey to be the representative of a larger area. Additionally, the individual species within an area designated as one vegetation type may vary.

4.13.3.11. Bureau of Meteorology Geofabric

The Bureau of Meteorology Australian Hydrological Geospatial Fabric (Geofabric[1]) consists of a number of GIS layers which include hydrological features such as rivers, water bodies, aquifers, and catchments. The current geofabric includes (Bureau of Meteorology, 2015):

- Geofabric Surface Cartography - Cartographic representation of surface hydrological features;

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[1] http://www.bom.gov.au/water/geofabric/index.shtml

- Geofabric Surface Network - Network representation of hydrological features;
- Geofabric Surface Catchments - Catchment boundaries derived from the 9 second Digital Elevation Model;
- Geofabric Groundwater Cartography - Cartographic representation of groundwater hydrology features;
- Geofabric Hydrology Reporting Catchments- Contracted nodes, contracted catchments and node-link network; and
- Geofabric Hydrology Reporting Regions - Reporting regions based on aggregations of contracted catchments.

It is worth noting that the catchment area is a function of the scale at it was estimated and therefore is likely to have inaccuracies at a fine scale. The current data is based on a 9 Second DEM and GA GEODATA TOPO 250K Series 1 (GEODATA 1) and GEODATA TOPO 250 K Series 3 (GEODATA 3).

Subsequent versions of the Geofabric will have upgrades to data and include (Bureau of Meteorology, 2015):

- hydrometric monitoring features;
- more detailed surface water hydrology; and
- Digital Elevation Model (DEM) derived streams and catchment boundaries based on a 1 second resolution DEM.

4.13.3.12. Soil Data

Some hydrologic models require information on the catchment soil properties (for example, information on the A and B horizon depths and their water holding capacity, or the soil type) to estimate losses from the rainfall.

Soil property data is available spatially for the whole country from the Atlas of Australian Soils (McKenzie et al., 2000); this information is available in a GIS format from the Australian Soil Resource Information System website. These maps are broad scale (typically 1:250000 - 1:500000) and were completed between 1960 and 1968. State based maps are available, also. Care should be taken when using soil maps as variations in soil over short distances occur frequently and cannot be resolved by the reconnaissance style mapping used in their development (McKenzie et al., 2000).

While it is possible to estimate land subject to inundation by floods through consideration of the soils and geomorphology, this does not provide any guidance on the likelihood of the flood hazard and therefore can be misleading. Furthermore, there is a need to ensure that the soil and geomorphoric data is obtained at a fine scale to ensure spatial variations over short distances are adequately recognised when using soil information to assess potential flood hazard.

4.13.3.13. Property Data

In order to assess the magnitude of the flood hazard to people and property, property data (including building type, condition and floor level) typically are required.

Property databases form the basis of most flood damage assessments. These databases typically require a description of the property attributes and features on a property by property basis. Typical information required for each residential property includes:

- Street address;
- Representative ground level;
- Habitable Floor levels;
- Building construction type (e.g. brick veneer, timber, slab on ground, on piers etc);
- Building age;
- Single/double storey; and
- House size.

Commercial and industrial properties require similar information, but also require information on the type of business undertaken at the site as this can have a significant bearing on the value of flood damages from business to business.

Ideally, this data are collected via field survey. However, it can be a costly process depending upon the number of properties for which data are required. Alternatively, there may sometimes be records available from the local authority, other government agency or the census. For broad assessments, property data may be estimated. A panel of people with relevant skills should review the method of estimation for soundness. As an example, property data may be estimated from aerial photography or from a general understanding of local conditions.

A number of national data sets are also available from Geoscience Australia such as:

- Australian Flood Risk Information Portal (Geoscience Australia) will be a central depository for information on flood studies conducted throughout the country and associated spatial data;
- Water Observations from Space historical surface water observations derived from satellite imagery for all of Australia for the period of 1998 to 2012; and
- State borders, city locations, topographic maps.

4.14. Other Data Considerations

4.14.1. Storage of Data and Meta-data

Most large data sets on a project are produced by combining multiple sources of information. Most large data sets are too big to be checked and must be machine quality controlled. It is important that meta-data associated with quality checking is recorded to assist future users of the data set.

4.14.2. Co-ordinate Systems and Datums

Most large national data sets are in latitude and longitude. Smaller data sets are in Map Grid of Australia (MGA 94) which is Universal Transverse Mercator projection and the Geocentric Datum of Australia 1994. Some older data sets may use ISG - Integrated Survey Grid or

AMG - Australian Map Grid. Care should be taken when translating from one projection to another; of particular concern is the use of the correct local conversion as these conversions are not the same across the country.

4.15. Other Hydrological Data

4.15.1. Tidal Data

In many coastal areas and areas adjacent to coasts, ocean and tidal data can be an important component of the design flood estimation process. Tidal data may be collected by manual observations or by automatic recorders and needs to include astronomical tides as well as storm surge and long-term trends in sea levels. In some circumstances, wave data may also be relevant.

Historical tidal data for particular events can be useful model calibration while long-term records can be used for statistical analysis for design flood estimation purposes (refer to Book 6, Chapter 5). With increased sea levels induced by global warming, it is likely that long-term records of tides and sea levels will exhibit non-stationary behaviour; refer to Book 1, Chapter 6[2] .

Tidal data is collected regularly by relevant government agencies, being concerned for the coastal environment or engineering. This data is published in handbooks or websites. In addition, there are research or other short-term projects carried out in coastal areas, which may include data on tides. However, these projects are generally localised and of short duration.

4.15.2. Meteorological Data

As well as rainfall and other precipitation, other meteorological data is used in water resources studies. This data is used to assess soil moisture and evapotranspiration for example. This data includes pan evaporation, temperature, humidity, wind speed and other parameters.

The Bureau of Meteorology is the principal agency that collects this data, however there are records held by water agencies and agricultural departments as well as small localised records held by different organisations. Regional maps of key meteorological data, especially pan evaporation and evapotranspiration are published by the Bureau of Meteorology, and this regional information is often adequate for many requirements.

Meteorological data is usually available free of charge from the Bureau of Meteorology and major agencies.The records from other organisations may be difficult to locate and then there may be contractual difficulties in obtaining and using the data.

4.15.3. Sediment Movement and Deposition

Sediment movement, including scour and deposition, is one of the most important water quality impacts of drainage systems, both natural and man-made and can cause environmental problems in downstream receiving waters as well as damage and disruption to drainage systems.

Data collection on sediment movement is particularly difficult and there is only limited available data. Most routine data collection programmes are carried out by water and

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[2] This section was written before the latest climate change guidance in Book 1, Chapter 6 (2024). A minor change to the text has been made to reflect the change in guidance.

environmental agencies, but these are usually somewhat limited. Tthere are some small specialised programmes carried out for specific projects, often as part of an environmental impact study. However these programmes are generally limited in scope and also limited in the duration for the data collection programme.

This data is normally available only directly from the agency or organisation that collects the data, and may be difficult to find that it exists and then it may be difficult to obtain.

Once data is located, it is then often difficult to access and use because of differences in the methods adopted for collection, analysis and processing. There are also differences in the treatment of bed and suspended loads and measurements of turbidity, all of which are used at times to measure sediment movement.

Sediment deposition may be monitored by owners of affected assets, but the data is difficult to apply in investigations.

Therefore application of sediment movement and deposition data is difficult and needs considerable skill to interpret and apply. Where this is an important aspect of a project, efforts should be exerted to find and use the data.

4.15.4. Water Quality

As well as sediment, there are many other water quality parameters that are relevant to water resources and drainage programmes. The water quality parameters that can be monitored cover a wide range from the relatively routine such as nutrients and salinity to quite specialised contaminants.

As with sediment, data collection on this topic is particularly difficult and there is only limited available data. Most data collection programmes are carried out by water and environmental agencies, and some of this data (especially the routine parameters, such as salinity) is available in formal data archiving systems. In addition to these programmes, there are some small specialised programmes carried out for specific projects, often as part of an environmental impact study.

Some types of water quality data, especially salinity and nutrients are available as historical records that can be used to calibrate models and assess changes in conditions with time, but much of the data is short term and variable. Considerable skill and expertise is needed to apply this data to project requirements.

4.16. Climate Change Data

In this section, data available to consider the impacts of climate change on estimation of design rainfalls and floods is described. As further research and development of climate change data occurs, the discussion and guidance presented here will change. Practitioners, therefore, should ensure that they are aware of these changes and the impact on available data.

4.16.1. Types of Climate Change Data

Quantifying the effects of climate change on the factors that affect flood estimation is a difficult task, and any estimates of impacts of future climate on the inputs to flood assessments will include large uncertainties. The fact that the occurrence of flood events, and their associated causal factors, is rare limits the data available to assess changes in their frequency or intensity (IPCC, 2012).

Observed data is often used to investigate whether there are any trends apparent in historical flood data. The data used to project the impacts of future climate on flooding is generally sourced from climate modelling. “Any useful technique for the assessment of future risk should combine our knowledge of the present, our best estimate of how the world will change, and the uncertainty in both” (Hunter, 2007). To study the impact of climate change, a plausible and consistent description of a possible future climate is required. The construction of such climate change scenarios relies mainly on results from model projections, although some information from past climates can be used (IPCC, 2001). Refer to Book 1, Chapter 6 for more information on climate change and flood estimates.

4.16.1.1. Observed Data

Stationarity is one of the fundamental assumptions in traditional design flood estimation. Climate change challenges this assumption as observed historical rainfall and flow data may not be a good indicator of future conditions. This has implications for the use of historical data in assessment of flood risk including in estimation of design rainfalls, flood frequency analysis, sea-level and storm surge, and estimates of design flood model parameters that account for losses.

Detecting changes in the frequency or intensity of precipitation or flood events in recorded data presents a number of difficulties (Jones et al., 2012; Milly et al., 2008). The ability to assess climate-driven observed changes in the magnitude and frequency of floods at regional scales is limited by the lack of observed records and their coverage in space and time, and by changes in catchments due to land-use and development (IPCC, 2012). Attributing trends in discharge data to climate change is particularly difficult, as changes in catchment conditions, or river operations can contribute to trends in the data (Bates et al., 2008). Long-term records are needed to be able to detect trends in data, and the availability of consistent, quality controlled data is a major limitation in any study to detect trends in large to extreme rainfall or flood data (Bates et al., 2008). There is evidence that climate change will result in a larger increase in extreme sub-daily rainfalls than at a longer duration (Westra, 2011). The availability of long records of sub-daily rainfall data is limited, with an average length of Australian sub-daily rainfall stations of approximately 19 years compared to an average length of 65 years for daily rainfall stations (Johnson et al., 2012).

One of the most fundamental issues in detecting trends in precipitation or discharge data due to climate change is separating the influences of climate variability from long-term climate change in a relatively short record. Due to the normal range of climate variability, there is limited information available to establish the probability of a flood event currently, even without consideration of climate change (White et al., 2010). Local and regional changes in precipitation due to climate change are greatly affected by patterns of atmospheric circulation. Patterns of change in precipitation associated with ENSO can dominate the global patterns of variations, particularly in the tropics and over much of the mid-latitudes (Trenberth, 2011). There is little observed data available to investigate relationships between hemispheric scale modes of the atmosphere (such as ENSO) and climate change.

The observed data available to directly estimate the impacts of climate change on antecedent conditions includes seasonal rainfalls, evapotranspiration, and soil moisture. Detecting changes in these parameters can be undertaken with a trend analysis, however long records with appropriate spatial coverage are required for this task. As for detecting changes in extreme precipitation or discharge events, the difficulty is in separating the impacts of climate change from natural variability or the influence of changes in catchment conditions, in the relatively short records available. The coverage of directly measured evapotranspiration data is relatively sparse across Australia and is very limited globally (Bates et al., 2008). Evapotranspiration data available from global analysis data is sensitive to the type of analysis and the uncertainty in the data makes it unsuitable for trend analysis (Bates et al., 2008). Direct measurements of soil moisture are available for only a few regions and are often very short in duration (Bates et al., 2008).

Changes in storm surge events can be investigated using data from tide gauge records. Tide gauge data can be used to evaluate the Annual Exceedance Probabilities of extreme sea levels, however a reliable analysis of the risk of extreme events or trends in the data is limited by the short duration of records collected at many gauges. Church et al. (2006) found only two gauges of sufficient length for use in this type of analysis in Australia, and only nineteen records with lengths of 40 years or greater (and some of these were intermittent). The limited number of tide gauges means that there is no data available for large stretches of coastline, which inhibits the assessment of this hazard even under present climate conditions, let alone future conditions due to climate change (McInnes et al, 2007).

4.16.1.2. Climate Modelling

- **Global scale modelling**

Whilst observed historical data can be used to investigate trends, Global Climate Models (GCMs) are most often used to generate data to investigate the impacts of climate change into the future on a global or continental scale.

Climate models are mathematical representations of the climate system, expressed as computer codes and run on computers (IPCC, 2007). The models would be too complex to run on any existing computer if all variables in the climate system were explicitly included in the models, so simplifications are made so that the system has reduced complexity and computing requirements (IPCC, 2001). Outputs from GCMs cover many variables that impact the hydrologic cycle including precipitation, evaporation, soil moisture and sea level. GCMs have been developed by a range of international agencies. The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (2007) used climate modelling output from 23 different GCMs as the basis of their global assessment of climate change (IPCC, 2007). GCMs differ in their representations of climatology and thus using an ensemble including a range of GCMs can enhance the representation of specific weather patterns (Abbs and Rafter, 2009; Grose et al., 2010).

In order to address the uncertainty in future greenhouse gas emissions, a range of plausible futures are often run with the GCMs. IPCC (2007) developed a range of emissions scenarios (SRES emissions scenarios) that are commonly used with GCMs. The SRES emissions scenarios are divided into six families based on different likely emissions considering future technological and societal changes (Corney et al., 2010). The current GCM results for Australia can be accessed through the Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/en/) and the Climate Futures web tool (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-futures-tool/introduction-climate-futures/).

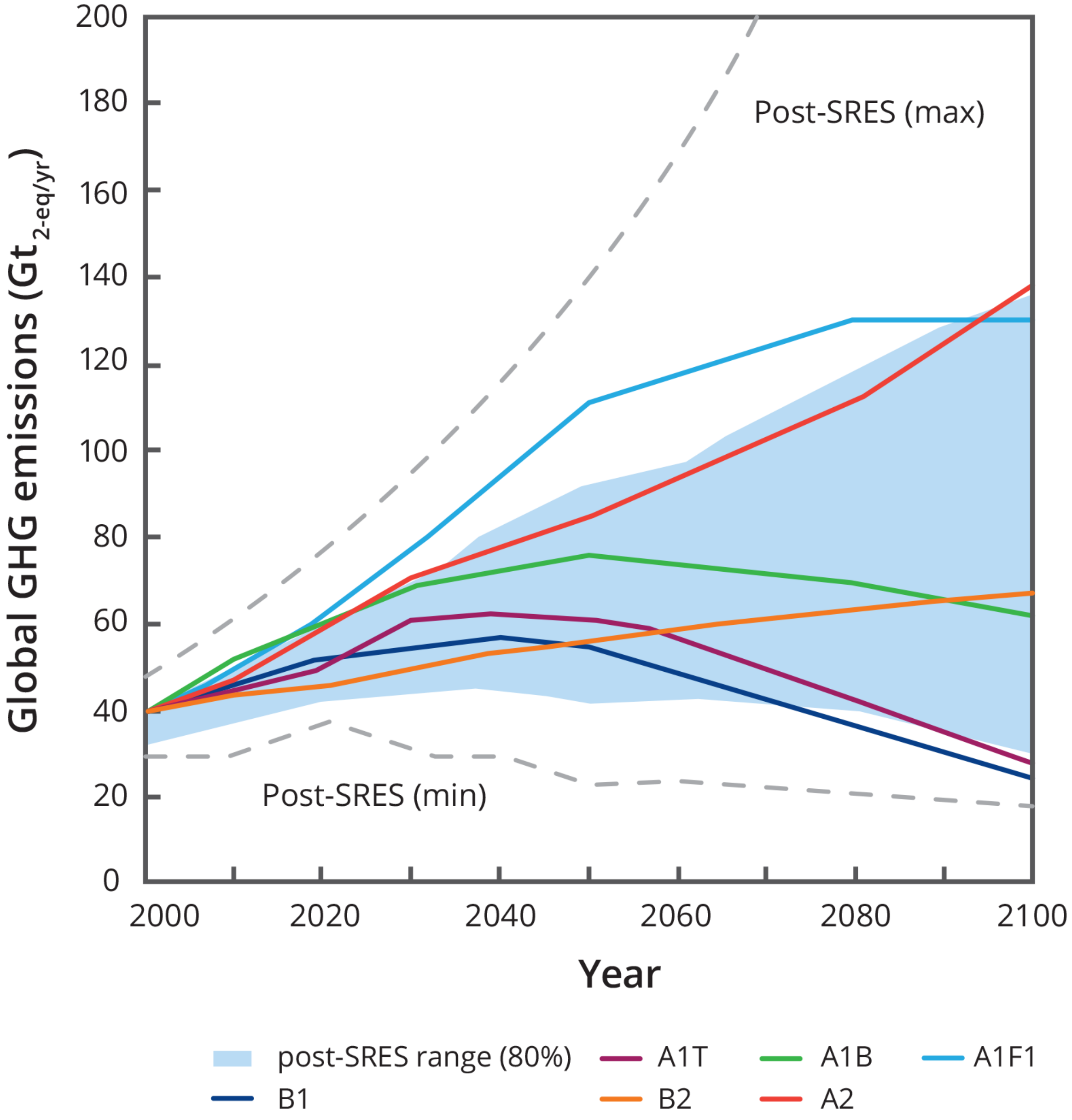

Figure 1.4.14. Global Greenhouse Gas Emissions Scenarios for the 21st Century (from IPCC, 2007)

- **Confidence in GCM data**

The fact that climate model fundamentals are based on established physical laws, such as conservation of mass, energy and momentum, along with a wealth of observations gives some confidence in the ability of models to represent the global climate. The models have shown a good ability to simulate important aspects of the current climate, and reproduce features of past climates and climate changes (IPCC, 2007).

Areas of uncertainty in the GCM projections include uncertainty in future levels of greenhouse gas emissions, the response of the climate to the emissions, and changes in regional climate (CSIRO, 2012). The cascade of uncertainties in projections is shown in Figure 1.4.15. The uncertainty in the levels of emissions results from a lack of knowledge of the future social, economic and technological development of the world, and the associated greenhouse-gas emissions. The model uncertainty is due to deficiencies in the knowledge of the science of climate change, in setting initial conditions for the models, and in the representation of the global climate by the models (Hunter, 2007). There are also deficiencies in the simulation of tropical precipitation, the El Niño- Southern Oscillation and the Madden-Julian Oscillation. Most of these errors are due to the fact that many important small-scale processes cannot be represented explicitly in GCMs, and so must be included in approximate form as they interact with larger-scale features. This is partly due to limitations in computing power, but also results from limitations in scientific understanding or in the availability of detailed observations of some physical processes (IPCC, 2007).

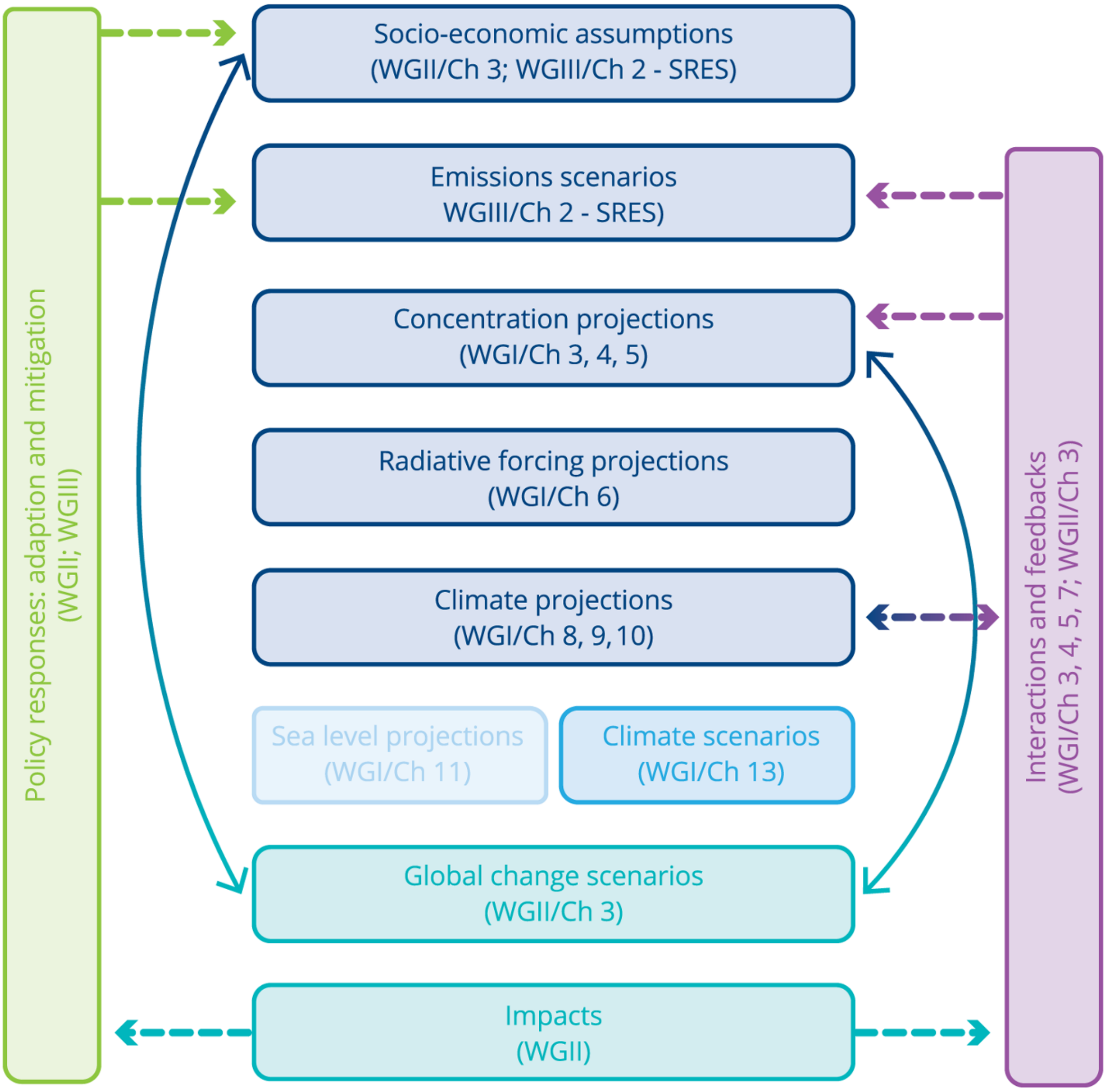

Figure 1.4.15. From (IPCC, 2001)

- **Regional Scale Modelling**

The outputs from GCMs give information at a global scale with a limited resolution, so cannot provide a detailed picture of climate variables at the regional scale required to investigate the factors influencing flood events (Corney et al., 2010). Some form of downscaling is required to investigate the impacts of future climate on specific variables at a local scale, in particular for precipitation and climate extremes. To address the decrease in confidence in the changes projected by global models at smaller scales, other techniques, including the use of regional climate models and downscaling methods, have been specifically developed for the study of local-scale climate change (IPCC, 2007). Three methods are commonly used to scale outputs from GCMs: temperature scaling, statistical downscaling, and dynamical downscaling (Westra, 2011). Combinations of these methods are also used.

- **Temperature Scaling**

Temperature scaling has been used give downscaled estimates of precipitation from GCMs. Extreme precipitation is directly related to the water holding capacity of the atmosphere. A warming climate leads to an increase in the water holding capacity of the air, which causes an increase in the atmospheric water vapour that supplies storms, resulting in more intense precipitation (Trenberth, 2011). The Casius-Clayperon relationship gives an increase of water holding capacity of approximately 7% per degree Celsius of warming (Trenberth, 2011). This relationship has been found to hold for some sub-daily rainfalls, however daily extreme rainfalls have been found increase at a lower rate (Lenderink and van Meijgaard, 2008). The relationship also appears to hold only to a threshold temperature (Hardwick-Jones et al., 2010). The simple scaling of rainfall with temperature does not reflect all the processes that produce rainfall events. The true scaling relationship is more complex and is affected by the extremity and duration of the rainfall event, the atmospheric temperature, and access to atmospheric moisture (Westra et al., 2013). This results in differing local impacts of climate change and, in particular, different impacts are seen dependent on the duration of the rainfall event.

- **Statistical Downscaling**

Statistical downscaling uses relationships between large-scale climate variables and local scale weather to develop estimates at a local scale. In the simulation of extreme rainfalls, a common approach is to use extreme value distributions to describe precipitation extremes (Abbs and Rafter, 2009). Another approach is to use a model to simulate precipitation and to then analyse the extremes (Mehrotra and Sharma, 2010). The advantage of statistical downscaling is that it is not computationally intense, and can be undertaken relatively quickly over large areas. The limitations of statistical downscaling include the assumption that the current observed relationships between large scale climate variables and local climate will persist in a changed climate regime. Another limitation is that the observational data set being used for the downscaling should cover the range of projected future climate responses (Grose et al., 2010).

- **Dynamical Downscaling**

Dynamical downscaling takes the outputs from a host GCM as inputs to either a limited area model or stretched grid global climate model. The result is a fine scale dynamical model over the area of interest, often called a Regional Climate Model (RCM). Because a RCM focuses on a small area, it can provide more detail over that area than is possible with a GCM alone (Grose et al., 2010). Dynamical downscaling allows representation of local scale features, such as orographic effects, land-sea contrast and other land surface characteristics, and smaller scale physical processes that influence extreme precipitation (Marauan et al., 2010). By modelling the atmosphere and local environment at a much finer scale than is possible using a GCM, it is expected that the specific processes that drive regional weather and climate will be better represented. Bias corrected outputs from dynamically downscaled models have been shown to be able to be used directly in projections of changes in extreme precipitation (White et al., 2010). A number of studies have used RCMs to investigate changes to daily precipitation extremes, however a lack of available sub-daily RCM data has limited studies on shorter duration events (Hanel and Buishand, 2010). The advantages of dynamical downscaling are in the ability to represent changes in rainfall spatial and temporal patterns, as well as impacts of local scale features. The disadvantage of dynamical downscaling is in computational time. There are assumptions inherent in the structure of each RCM and ideally a range of RCMs would be used in conjunction with a range of GCMs to give a more comprehensive description of local climate. The ability to undertake such studies is inhibited by the computational intensity of the task, and thus studies are generally limited to use of one or two RCMs with a range of GCMs.

4.17. References

ANZLIC (2008), ICSM Guidelines for Digital Elevation Data Version 1, August 12.

Abbott, M.B. (1991), Hydroinformatics - Information Technology and the Aquatic Environment, Avebury Technical, Aldershot, UK.

Abbs, D. and Rafter, T. (2009), Impact of Climate Variability and Climate Change on Rainfall Extremes in Western Sydney and Surrounding Areas: Component 4 - dynamical downscaling, CSIRO.

Ball, J.E. and Cordery, I. (2000), Information and hydrology, Proc. Hydro 2000 - Hydrology and Water Resources Symposium, Perth, WA, Australia, pp: 997-1001.

Bates, B. C., Z. W. Kundzewicz, S. Wu, and J. P. Palutikof (2008), Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, Rep., 210 pp, IPCC Secretariat, Geneva.

Beynon-Davies, P. (2002), Information Systems: An introduction to informatics in organisations, Basingstoke, UK: Palgrave Macmillan. ISBN 0-333-96390-3.

Boyer, M.C. (1964) Streamflow measurement, Handbook of Applied Hydrology, Ed. V. T. Chow, Chapter 15, McGraw-Hill.

Bureau of Meteorology (2015), Australian Hydrological Geospatial Fabric (Geofabric). [ONLINE] Available at: http://www.bom.gov.au/water/geofabric/index.shtml. [Accessed 18 August 15].

CSIRO (2012), Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), CSIRO, Australia, September 2012, 41 pp.

Chow, V., Maidment, D. and Mays, L. (1988), Applied hydrology. New York: McGraw-Hill.

Church, J.A., Hunter, J.R., McInnes, K.L. and White, N.J. (2006), Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. Aust. Met. Mag., 55(4), 253-260.

Cordery, I., Weeks, B., Loy, A., Daniell, T., Knee, R., Minchin, S. and Wilson, D. (2006), 'Water Resources Data Collection and Water Accounting', Australian Journal of Water Resources, 11(2), 257-266.

Corney, S.P., Katzfey, J.J., McGregor, J.L., Grose, M.R., Bennett, J.C., White, C.J., Holz, G.K., Gaynor, S.M. and Bindoff, N.L. (2010), Climate Futures for Tasmania: climate modelling technical report, Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart, Tasmania.

Fenton, J.D. (2001), Rating curves: Part 1-Correction for surface slope. OR Fenton, J.D. (2001) Rating curves: Part 2-Representation and approximation.

Fenton, J.D. and Keller, R.J. (2001), the Calculation of Streamflow from Measurements of Stage, Technical Report Report 01/6, Cooperative Research Centre for Catchment Hydrology, Monash University, Clayton, Vic, Australia.

Grose M.R., Barnes-Keoghan I., Corney S.P., White C.J., Holz G.K., Bennett J.B., Gaynor S.M. and Bindoff N.L. (2010), Climate Futures for Tasmania: general climate impacts technical report, Antarctic Climate & EcosystemsCooperative Research Centre, Hobart, Tasmania.

Hanel, M. and T.A. Buishand (2010), On the value of hourly precipitation extremes in regional climate model simulations, Journal of Hydrology, 393: 265-273.

Hardwick-Jones, R, S.Westra and A. Sharma (2010), Observed relationships between extreme sub-daily precipitation, surface temperature and relative humidity, Geophysical Research Letters, 37(L22805).

Herschy, R.W. (1995), Streamflow Measurement, E & FN Spon, Chapman & Hall, London, UK. Huber and Dickinson, (1988)

Hersh, E. S. (2012), The long tail of hydroinformatics: Implementing biological and oceanographic information in hydrologic information systems.Hunter, J., (2007): Estimating sea-level extremes in a world of uncertain sea-level rise [http://staff.acecrc.org.au/~johunter/vic_flood_10102007_v12.pdf], 5th Flood Management Conference, Warrnambool, Australia, 9-12 October 2007.

Hunter, J. (2007), Estimating sea-level extremes in a world of uncertain sea-level rise, 5th Flood Management Conference, Warrnambool, Australia, [Accessed 12 October. 2007].

IPCC (Intergovernmental Panel on Climate Change) (2012), Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Socio-Economic Scenarios [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, V. Barros, C.B. Field, T. Zwickel, S. Schloemer, K. Ebi, M. Mastrandrea, K. Mach, C. von Stechow (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam Germany, p: 51.

IPCC (Intergovernmental Panel on Climate Change) (2001), Climate Change 2001, The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 p.

IPCC (Intergovernmental Panel on Climate Change) (2007), Climate Change 2007, Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 p.

ISO (International Standards Organisation) (2013), Guide: 18365:2013 Hydrometry. Selection, establishment and operation of a gauging station, International Standards Organisation.

Johnson, F., K.Haddad, A.Rahman, and J.Green (2012), Application of Bayesian GLSR to estimate sub daily rainfall parameters for the IFD Revision Project. Hydrology and Water Resources Symposium 2012, Sydney. Engineers Australia.

Jones, D.A., Wang, W. and Fawcett, R. (2007), Climate Data for the Australian Water Availability Project: Final Milestone Report. National Climate Centre, Bureau of Meteorology, Melbourne.

Jones, M.R., (2012), Characterising and modelling time-varying rainfall extremes and their climatic drivers. PhD Thesis, Newcastle University.

Kundzewicz Zbigniew, W. (2004), Editorial Hydrological Sciences-Journal-des Sciences Hydrologiques, 49(1), 3-6.

Lenderink, G. and E. van Meijgaard (2008), Increase in hourly precipitation extremes beyond expectations from temperature changes, Nature Geoscience, 1, pp: 511-514

Malleron, N., Zaoui, F., Goutal, N., and Morel, T. (2011), On the use of a high-performance framework for efficient model coupling in hydroinformatics. Environmental Modelling & Software, 26(12), 1747-1758.

Marauan, D.F., Wetterhall, A.M., Ireson, R.E., Chandler, E.J., Kendon, M., Widmann, S., Brienen, H.W., Rust, T., Sauter, M., Theme, V.K.C., Venema, K.P., Chun, C.M., Goodess, R.G., Jones, C., Onof, M., Vrac, I. and Thiele-Eich (2010), Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user, Reviews of Geophysics, 48.

McInnes, K.L., Hubbert, J.D, Macadam, I. and O'Grady, J.G. (2007), Assessing the Impact of Climate Change on Storm Surges in Southern Australia, In Oxley, L. and Kulasiri, D. (eds) MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, ISBN: 978-0-9758400-4-7.

McKenzie, N.J., Jacquie, D.W, Ashton, L.J., and Cresswell, H.P. (2000), Estimation of soil properties using the atlas of Australian soils, CSRIO Land and Water, Canberra ACT.

Mehrotra, R., and Sharma, A. (2010), Development and Application of a Multisite Rainfall Stochastic Downscaling Framework for Climate Change Impact Assessment, Water Resources Research, 46.

Meynett, A.E. and van Zuylen, H.J. (1994), On the concept of hydroinformatics, Proc. Hydroinformatics '94, Delft, The Netherlands, AA Balkema, pp: 19-24.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., bigniew, W.Z., Kundzewicz, Z.W., Lettenmaier, D.P. and Stouffer, R.J. (2008), Stationarity is Dead: Whither Water Management? Science, 319(5863), 573-574.

Moya Quiroga, V., Mano, A., Asaoka, Y., Kure, S., Udo, K., and Mendoza, J. (2013), Snow glacier melt estimation in tropical Andean glaciers using artificial neural networks. Hydrology and Earth System Sciences, 17(4), 1265-1280.

National Research Council (2004), Assessing the National Streamflow Information Program, National Academy of Sciences, US.

Pilgrim, DH (ed) (1987) Australian Rainfall and Runoff - A Guide to Flood Estimation, Institution of Engineers, Australia, Barton, ACT, 1987.

Popescu, I., Jonoski, A., and Bhattacharya, B. (2012), Experiences from online and classroom education in hydroinformatics, Hydrol. Earth Syst. Sci., 16: 3935-3944, doi: 10.5194/hess-16-3935-2012.

Rantz, S.E. (1982), Measurement and computation of stream flow. Volume 1: Measurement of stage and discharge; Volume 2: Computation of discharge. US Geological Survey water-supply paper, 2175, 631.

Raupach, M.R., Briggs, P.R., Haverd, V., King, E.A., Paget, M. and Trudinger, C.M. (2009), Australian Water Availability Project: CSIRO Marine and Atmospheric Research Component: Final Report for Phase 3, CAWCR Technical Report, No.013, July.

Simons, D.B. and Richardson, E.V. (1962), The effect of bed roughness on depth-discharge relations in alluvial channels, U.S. Geological Survey Water-Supply Paper 1498-E.

Stewardson, M.J. and Howes, E.A. (2002), The number of channel cross-sections required for representing longitudinal hydraulic variability of stream reaches. Proceedings of the 27th Hydrology and Water Resources Symposium. Engineers Australia, pp: 21-25.

Toppe, R. (1987), Terrain models - A tool for natural hazard Mapping, Avalanche Formation, Movement and Effects, IAHS Publication Number 162: 629-638.

Trenberth KE (2011), Changes in precipitation with climate change. Clim Res 47: 123-138.

Vathananukij, H and Malaikrisanachalee, S. (2008), Hydroinformatic system (implementation in Thailand), Water SA, 34(6), 725-730.

Wain, A.T., Atkins, A.S. and McMahon, T.A. (1992), The Value of Benefits of Hydrologic Information, AWRAC Research Project P87/24, Centre for Applied Hydrology, University of Melbourne, p: 59

Westra, S. (2011), Implications of Climate Change on Flood Estimation. Discussion Paper for the Australian Rainfall and Runoff Climate Change Workshop No.2, 5th November 2010, UNSW.

Westra, S., L.V. Alexander, F.W. Zwiers (2013), Global increasing trends in annual maximum daily precipitation. Journal of Climate, in press, doi:10.1175/JCLI-D-12-00502.1.

White, C.J., Grose, M.R., Corney, S.P., Bennett, J.C., Holz, G.K., Sanabria, L.A., McInnes, K.L., Cechet, R.P., Gaynor, S.M. and Bindoff, N.L. (2010), Climate Futures for Tasmania: extreme events technical report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.

World Meteorological Organization (2010), Manual on Stream Gauging - Volume I - Fieldwork, WMO-No. 1044, Geneva, Switzerland, ISBN 978-92-63-11044-2.

Chapter 5. Risk Based Design

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5.1. Introduction

Floods can cause significant impacts where they interact with the community and the supporting natural and built environment. However, flooding also has the potential to be the most manageable natural disaster as the likelihood and consequences of the full range of flood events can be understood enabling risks to be assessed and where necessary managed.

Design flood estimation plays a key role in understanding flood behaviour and how this may change with changes within the floodplain and catchment and in climate and how these changes can influence both decisions that influence the growth and management of flood risk.

Design flood estimation provide essential information on a range of key factors that need to be considered in understanding and managing the consequences of flooding. These include: flood frequency; flow rates, velocities and volumes; flood levels and extents; duration of inundation. ARR provides essential analytical tools to assist in estimating design floods and in understanding these factors. Estimates of design floods are an essential element in understanding flood behaviour and making informed decisions on:

- Managing flood risk through a risk based decision making process (AEMI, 2013). Such approaches generally provide an understanding of flood behaviour across the full range of flood events, up to and including extreme events, such as the Probable Maximum Flood (PMF). They can inform decision making in flood risk management, a broad range of land use planning activities, emergency management for floods and dam failure, and in estimating flood insurance premiums;

- Managing flood risk through the use of design standards related to the probability or frequency of occurrence, rather than the broader assessment and management of risk;

- Setting infrastructure performance criteria based upon a design standard, generally a probability or frequency of an event, rather than the broader assessment and management of risk;

- Managing flood risk in short term projects through a risk based decision making process considering the life of a project; and

- Understanding and managing the impacts changes within the catchment and floodplain may have on flood behaviour and risk.

This chapter provides advice and examples on using the analytical tools outlined in ARR to inform decision making for flood risk management, road and rail design, mining and agriculture and design of dams. It does not provide details on the design standards, risk assessment frameworks, the assessment of impacts on the community or built or natural environment, nor to estimate residual risks. Further information on risk management approaches, processes and frameworks can be found in (AEMI, 2013), ANCOLD (2003) ISO (2009a).

The remainder of this chapter is structured as follows:

- Book 1, Chapter 5, Section 2 provides a background on flood risk;
- Book 1, Chapter 5, Section 3 discusses risk analysis;
- Book 1, Chapter 5, Section 4 discusses managing risk;
- Book 1, Chapter 5, Section 5 discusses managing flood risk to communities;
- Book 1, Chapter 5, Section 6 discusses managing flood risk to mining, agriculture and infrastructure projects;
- Book 1, Chapter 5, Section 7 discusses the management of flood risk in relation to dams.;
- Book 1, Chapter 5, Section 8 discusses the management of flood risk using basins;
- Book 1, Chapter 5, Section 9 discusses the consideration of effective service life of infrastructure;
- Book 1, Chapter 5, Section 10 discusses how flood risk changes over time due to a range of factors;
- Book 1, Chapter 5, Section 11 provides further reading material;
- Book 1, Chapter 5, Section 12 provides some examples of calculations; and
- Book 1, Chapter 5, Section 13 provides references.

5.2. Flood Risk

Flood risk results from the interaction of the community, through human occupation or use of the floodplain, with hazardous flood behaviour. It is the risk of flooding to people, their social or community setting, and the built and natural environment (AEMI, 2013).

Flood risk is not simply the probability of an event occurring. The *International Standard on Risk Management,* (ISO, 2009a) defines risk as the effect of uncertainty on objectives. In addition, *ISO Guide 73:2009 Risk Management Vocabulary* (ISO, 2009b) notes that uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood. An effect is a positive or negative deviation from the expected outcome. Objectives can have different aspects (financial, health and safety, environmental) and apply at different levels (local, state, site).

AEMI (2013) and ANCOLD (2003) express risk in terms of combinations of the likelihood of events (generally measured in terms of Annual Exceedance Probability (AEP)) and the severity of the consequences of the event (see Figure 1.5.1). Risk is higher the more frequently an area is exposed to the same consequence or when the same frequency of event has higher consequences.

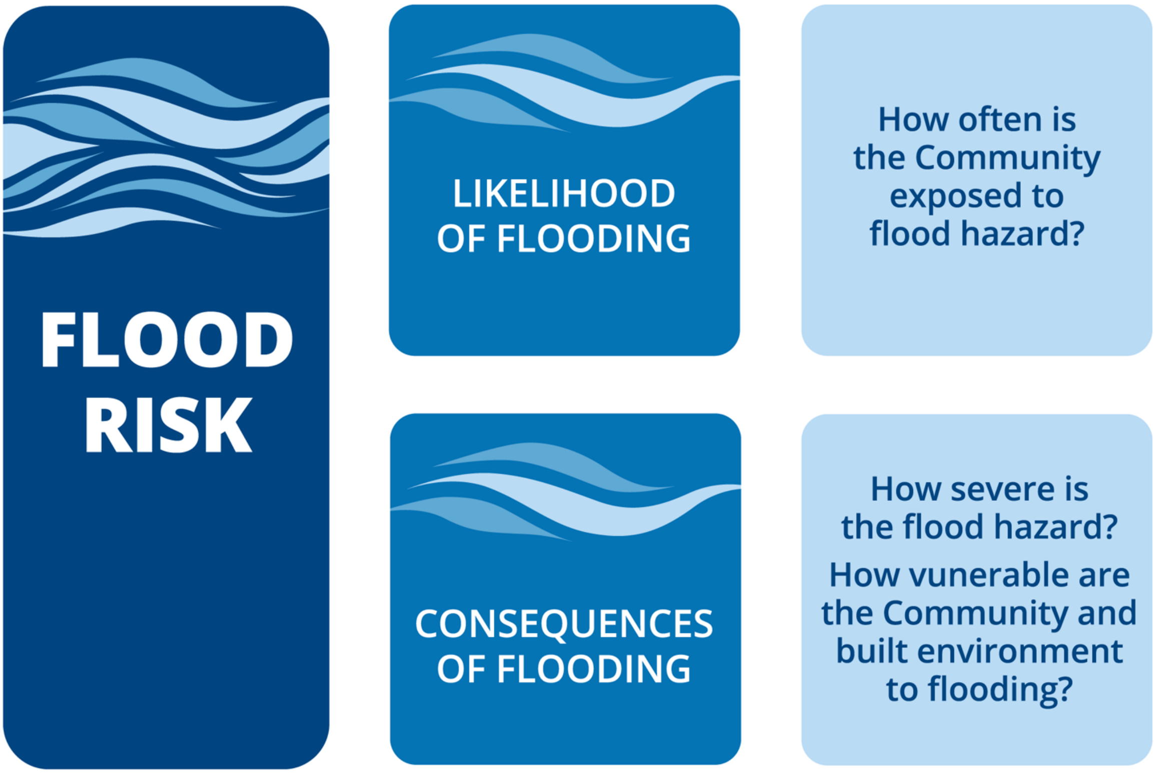


Figure 1.5.1. Components of Flood Risk (After McLuckie (2012)

AEMI (2013) discusses the consequences of flooding on the community. The consequences depend upon the vulnerability of the community and the built environment to flooding. Vulnerability varies with the element (people, property and infrastructure) at risk and within the different cohorts within the elements outlined below. *AEMI (2015)* advises that this may be measured in terms of the impacts upon:

- *People* – in terms of fatalities and injuries;
- *The economy and assets* - in terms of reduced economic activity and asset losses;
- *The social setting* – in terms of consequences to the community as a whole (rather than individuals) that can lead to the breakdown of community organisations and structures. This can include the temporary or permanent loss of community facilities or culturally important objects or events;
- *Public administration* – in terms of changes to the ability of the governing body for the community to be able to deliver its core functions;
- *The environment* – in terms of destruction and degradation of critical environmental assets (and their processes and structures) and/or species extinction and habitat range reduction; and

The consequence to different elements from the same exposure to flooding can be different. For example, a flood may have major consequences for community assets (such as a water or sewerage treatment plant) but have only minor or moderate consequences in terms of potential fatalities and injuries in the population.

The likelihood of exposure to flooding and therefore flood risk varies significantly between and within floodplains and flood events of different magnitudes. Figure 1.5.2 shows areas exposed to flooding from events of different AEPs.

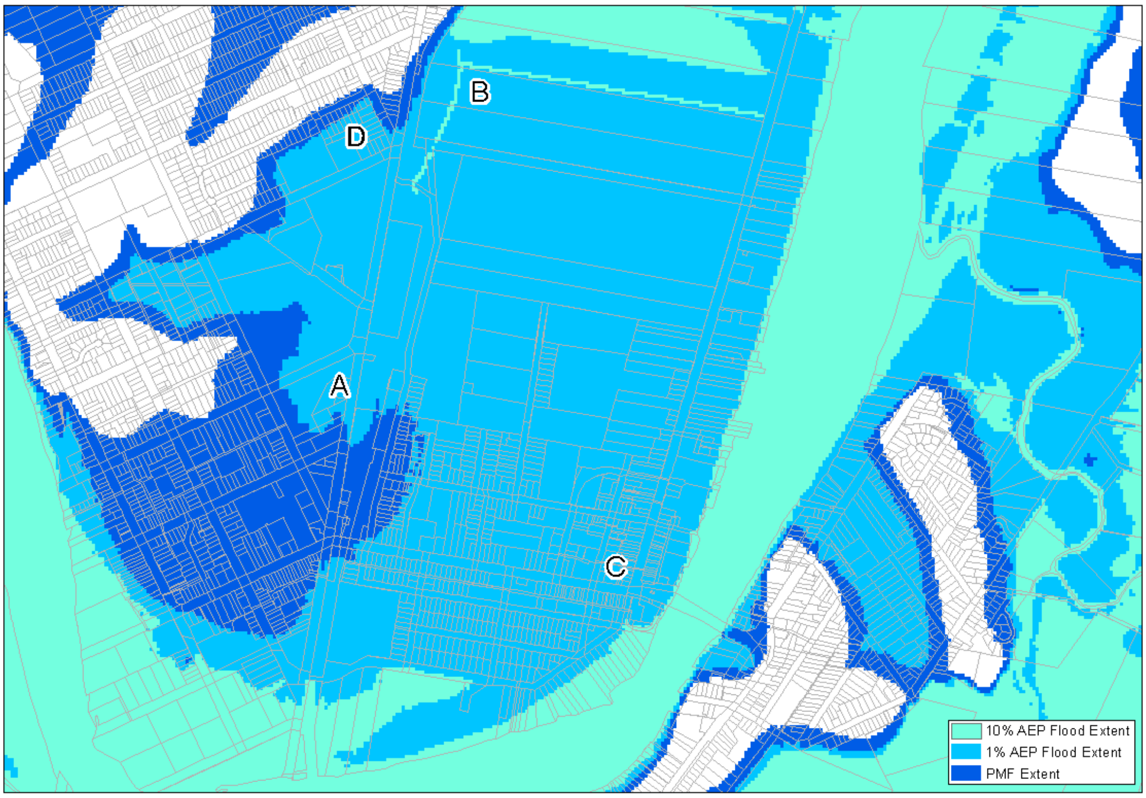


Figure 1.5.2. Map Showing Different AEP Flood Extents Including an Extreme Event

5.3. Risk Analysis

Risk analysis is a systematic approach to understanding the nature of and deducing the level of risk. It involves developing an understanding of the nature of, driver for, hazard and the associated consequences to rank the relative severity of risk. It is one of the steps in the risk management process (ISO, 2009a) and for example is generally undertaken as part of a floodplain management study in the flood risk management framework *(AEMI, 2013).*

Risk analysis involves understanding the varying likelihood of events (that result in a consequence), and the severity of their consequences. It should also involve an assessment of confidence, which considers factors such as the divergence of opinion, level of expertise, uncertainty, quality, quantity and relevance of data. These factors are combined to assign a relative risk rating for an event through development of a risk matrix or other tools. Risk analysis may be quantitative or qualitative. In both cases the probability of events affecting communities may be able to be estimated through design flood estimates.

Quantitative analysis is often used where both the probability and the consequences can be measured. For example, consequences may be estimated in terms of tangible flood damage to the community for events of different AEPs. Tangible damages are those damages that are more readily able to be estimated in economic terms and lend themselves to quantitative assessment, including:

- Direct damages to structures and their contents due to water contact; and
- Indirect damages of clean-up of debris and removal of damaged material, loss of wages, sales, production and costs of alternative accommodation, and opportunity costs due to loss of services.

Qualitative analyses are generally undertaken where consequences are difficult to quantify. For example, these can include social and environmental impacts and the costs of fatalities and injuries which are intangible damages that cannot readily be put in economic terms. Table 1.5.1 provides an example of a qualitative risk matrix.

Table 1.5.1. Example Qualitative Risk Matrix

Consequence Level					
Likelihood Level	Insignificant	Minor	Moderate	Major	Catastrophic
Almost Certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	Extreme	Extreme
Unlikely	Low	Low	Medium	High	Extreme
Rare	Very Low	Low	Medium	High	High
Very Rare	Very Low	Very Low	Low	Medium	High
Extremely Rare	Very Low	Very Low	Low	Medium	High

Risk analysis can be used to inform decisions on both the acceptability of residual risk and the effective and efficient use of scare resources to better understand and manage risk.

5.4. Managing Flood Risk

Managing flood risk generally involves a combination of:

- Managing changes within the floodplain that may alter flood behaviour;
- Altering the likelihood (how frequently exposure to flooding occurs); and
- Managing the consequences of flooding (reducing vulnerability to flooding when exposed) to reduce the risks.

Managing risk needs to consider the different elements at risk which may require different management techniques and standards. It also needs to consider the risks to the existing community and built and natural environment and the additional risk created by introducing new development and infrastructure into the floodplain.

5.4.1. Managing Changes to Flood Behaviour

Changes within the floodplain that can significantly affect flood behaviour include:

- Development (including filling) within the floodplain (particularly in flow conveyance and flood storage areas);
- Development within the catchment even though outside the floodplain; and

- Construction or upgrade of above ground infrastructure across waterways and the floodplain.

These activities may result in significant changes to flood behaviour including changes to flow paths, peak flow and velocities, flood levels and extents, distribution of flood waters, and the timing and duration of flooding. These changes can lead to adverse impacts on the existing community and the built and natural environment and the built and natural environment through changes to flood behaviour and the ability of the community to effectively respond to flood emergencies.

New developments and infrastructure projects generally have constraints placed on them through government approvals processes relating to negating or minimising adverse impacts of the project on existing development and the environment.

Broader processes such as the floodplain specific management process AEMI (2013) often examine changes through scenario testing. These may be managed though floodplain, catchment or community based techniques as discussed in Book 1, Chapter 5, Section 5.

However decisions on infrastructure projects, particularly those developed by entities that do not manage floodplain or catchment development, are often made without being able to influence development directions or mitigation efforts. Therefore decisions of infrastructure projects, may need to consider these potential changes as part of non-stationarity considerations as part of project investigations. This is discussed in Book 1, Chapter 5, Section 10 of this chapter.

5.4.2. Managing Flood Risk by Limiting Likelihood and Consequences

Approaches to managing the likelihood or consequences of flood risk on or to a community or asset generally fall into the following types:

- Use of design standards that relate to a particular flood event;
- Providing a certain level of service; and
- Use of risk based management approaches.

Risk based management approaches are generally more complex than the use of design flood and level of service standards.

5.4.2.1. Design Flood Standards

The establishment of design flood standards for infrastructure design and as a basis for minimum protection levels for the community have often been based upon decisions to reduce the frequency of exposure to risk. This involves a balance between protection of an asset or affected communities and stakeholders from an event against the cost of the infrastructure to provide protection.

Design flood standards are generally aimed at limiting the frequency of exposure to flood risk. For example, the use of a minimum floor levels for a building relative to a design flood level aims to reduce the exposure to flooding by excluding flooding from above the floor level of the building in the design flood event. This approach is based upon accepting that consequences that result from the building flooding in events larger than the design flood event.

Design flood standards are typically adopted across an entire floodplain, or government service area. Generally, there is only limited ability to incorporate location specific issues into the design flood standards.

When used in isolation, this approach makes the assumption that the residual risks remaining after development is constructed to standards are acceptable. It also assumes that:

- the location is suitable for the development;
- the development will not impact upon flood behaviour and therefore have an adverse impact elsewhere in the community; and
- the impacts of flooding on the building and its occupants, including the associated residual risks, are acceptable or can be managed by other means.

Where used in isolation this can limit the effectiveness of this approach and may lead to decisions that leave individuals, communities and the built environment exposed to risks that may be considered unacceptable to the community.

Design flood standards are also generally based upon existing floodplain, catchment and climatic conditions, what can be called stationary conditions. However, these conditions can change over time. Consideration in estimating design floods is discussed in Book 1, Chapter 5, Section 5 to Book 1, Chapter 5, Section 5. Further discussion on the factors that can lead to non-stationarity and current literature on non-stationary risk assessment is provided in Book 1, Chapter 5, Section 10.

5.4.2.1.1. Design Flood Standard Terminology

There are two key ways in which design flood standards are typically expressed:

- Annual Exceedance Probability (AEP): the likelihood of occurrence of a flood of a given size or larger in any one year; usually expressed as a percentage (e.g. a flood protection levee may adopt of Flood Design Standard that offers protection up to the a 1% AEP event); and
- Service Life Exceedance Probability (SLEP): The likelihood of exceedance during a project's adopted service life, rather than as an annual likelihood. It is recommended that this should be the Effective Service Life (Book 1, Chapter 5, Section 9), rather than the Design Service Life.

AUSTROADS, the national association of road transport and traffic authorities in Australia use both the SLEP approach and the AEP method depending on the context.

The AEP method is used to define the levels of service of roads:

“Freeways and arterial roads – should generally be designed to pass the 50 or 100 year ARI flood without interruption to traffic. However for arterial roads in remote areas, a reduced standard is commonly adopted where traffic densities are low, Austroads (1994).”

The SLEP method is used in the design of bridges:

“All bridges are to be designed so that they do not fail catastrophically during a flood that has a 5% chance of being exceeded during the Design Service Life of the structure. Assuming a 100 year Design Service Life, this equates to a flood with an ARI of 2000 years’ Austroads (1994).”

It is considered that while design standards are commonly expressed as an annual exceedance probability, it may be the case that stakeholders actually interpret and apply this more as a SLEP or an Exceedance Frequency over the adopted service life. For example, when stakeholders refer to a 1% AEP flood standard (floor level) for residential developments, conceptually they may interpret this to mean that the floor level for the property will only be exceeded once in every 100 years.

The SLEP approach may be more readily understandable for short term or temporary structures (refer to Book 1, Chapter 5, Section 6). Similarly, where infrastructure may be particular susceptible to damage from overtopping (e.g. a bridge superstructure that is not designed for inundation or a secondary spillway), then it may be important to understand the likelihood of being exceeded during the structure's effective service life (discussed in Book 1, Chapter 5, Section 9).

5.4.2.2. Level of Service Standards

Level of service standards are generally aimed at maintaining the serviceability during an event of a particular magnitude. For example, having a road trafficable in a design flood event of a certain AEP or having a waterway structure under the road pass the peak of a design flood event without overtopping the road. Considered in isolation, this approach assumes that the:

- Road will not impact upon flood behaviour and have adverse impact on the community;
- Impacts of flooding on the road are acceptable or can be managed by other means. For example, the road is expected to overtop and the design allows for damage minimisation or replacement in such events;
- Level of service provided is acceptable. For example, loss of access along the road is expected during a flood event and this is considered in emergency management planning; and
- Residual risk remaining to the community is acceptable.

Similarly to design flood standards, the assumptions of this approach can limit its effectiveness, particularly where it is used in isolation.

5.4.2.3. Risk Based Decision Making Processes

Risk based decision making processes (such as those outlined in AEMI (2013)) are used to develop management strategies that consider the risks associated with a full range of potential flood events and the associated consequences to the community and its supporting built and natural environment. It can be used to:

- manage the residual risks associated with design flood standards, or
- for management of risks for non-standard and critical infrastructure where a broad design flood standard may not be appropriate.

5.4.2.3.1. Non-Standard or Critical Infrastructure

Some examples of this type of infrastructure include:

- Dam safety risks (ANCOLD, 2003), and design of spillways and outlets;

- Risk management decisions for projects with a relatively short time frame, such as construction projects as well as temporary infrastructure (such as a coffer dam during construction);
- Structures that are particularly susceptible to overtopping or inundation. For example, a bridge superstructure that cannot withstand active flow or impacts from debris, or a flood levee that is not designed for overtopping and will likely result in failure.
- Critical infrastructure that may result in significant consequences should they fail or be inundated. This may include economically important infrastructure (for example transportation routes such as those between ports and major economic hubs, trunk communication networks (internet, phone) or key elements of the electricity network) or emergency response infrastructure (e.g. hospitals, evacuation centres etc).

In undertaking a risk based design process to develop management strategies for non-standard and critical infrastructure, it is important to understand the stakeholders involved in the decision making process. In many cases, these stakeholders may have different risk preferences (risk averse versus risk accepting). For example, a mining company may have a different risk preference for inundation of a mine, versus the community preferences for flood impacts downstream of the mine. It will be important to fully understand these different preferences to assist in informing the appropriate mitigation measures that might be required as the same likelihood and consequences could lead to a higher risk categorisation where there is a risk averse rather than a risk accepting preference.

5.4.2.3.2. Management of Residual Risk

When examining risks to existing and future development within a community the approach can be used in a manner that is complementary to the use of design flood and levels of service standards by examining the residual risk to the community and examining whether additional risk management measures may be necessary. This approach may involve testing whether the design flood or level of service standard is appropriate in the circumstances or whether additional management measures may be warranted to address residual risks.

For example, in a particular instance the use a design flood event as a standard for development within a community may reduce the frequency of exposure of people and property to flooding. However, additional management measures may be required to address residual risks. For example:

- the degree of flood damage to new buildings built to design standards mean that risks to property remain high. This may result in consideration of the use of a larger design flood event as a standard for development or other damage reduction approaches to broadly reduce flood damages.
- limitations to the ability to effectively warn and evacuate the community during the available warning time may mean that risk to life may remain high. Implementation of options to reduce risks to life, such as:
  - Development or improvement of a flood warning system so the community can be advised of a flood event and have more time to respond to calls for evacuation; or
  - Upgrade of evacuation routes to improve traffic capacity to enable the community to be more effectively evacuate within the available warning time.
- the effect development has on flood behaviour outside the development area may be significant. This may result in the need to implement, additional management measures

such as allowance in design for areas within the floodplain to continue to provide their essential flood conveyance and storage functions.

5.5. Managing Flood Risks to Communities

Flooding has the potential to be the most manageable natural disaster as the location of flood impacts and its effect upon the community and the built and natural environment can be understood for the full range of events.

Best practice in flood risk management in Australia (AEMI, 2013) works towards the vision:

“Floodplains are strategically managed for the sustainable long-term benefit of the community and the environment, and to improve community resilience to floods.”

Best practice promotes the consideration and, where necessary, management of flood impacts to existing and future development to improve community flood resilience using a broad risk management hierarchy of avoidance, minimisation and mitigation to: reduce the health, social and financial costs of occupying the floodplain; increase the sustainable benefits of using the floodplain, and improve or maintain floodplain ecosystems dependent on flood inundation (AEMI, 2013).

Managing flood risk provides an informed basis for the effective and efficient use of scare resources to:

- Better understand flood risk;
- Manage the growth in flood risk to the community due to the introduction of new development into the floodplain; and
- Reduce risks to the existing community where warranted.

This enables investment to be focused on understanding and managing flood risk where the need and benefit is greatest.

Different treatment solutions may be necessary depending upon the element at risk (people, property and infrastructure) and the location. Treatment options may involve a combination of flood mitigation, emergency management, flood warning and community awareness, together with strategic and development scale land-use planning arrangements that consider the flood situation and hazards.

Different options are also used dependent upon whether the aim is to manage risk to existing or future development within the community.

For the existing development it is important to understand the current exposure of the community to the full range of flooding, how the associated risks to different elements within the community are currently being managed and whether changes would be required to reduce risks to a more acceptable level. Where treatment options to reduce risks are being considered the impacts these measures may have on flood behaviour need to be understood and considered in decision making.

For flood risk to future development it is important to understand how the flood behaviour varies across the floodplain so that the constraints that this may place on development can be considered in deciding where to develop (and where not to develop), the types of development that may be suitable in different areas, and the flood related development constraints necessary to reduce risks to acceptable levels (in areas suitable for development).

It is also important to consider how flood behaviour and the associated risk will change over time due to development in the catchment and due to climate change and its impacts on both sea level and the intensity of flood producing rainfall events (discussed in Book 1, Chapter 6). Assessment of these changes on design flood estimates are discussed in Book 1, Chapter 5, Section 5 to Book 1, Chapter 5, Section 5.

More information on understanding and managing flood risk is available in AEMI (2013).

5.5.1. Using Flood Estimation to Inform Flood Risk Management

Design flood estimation can support management of flood risk to the community by improving knowledge of the potential range of flood behaviour and providing tools and information to support decision making. The selection of a modelling approach needs to consider the capability the approach provides relative to the requirements of the project specification. Many management decisions, such as emergency management planning, rely upon an understanding of the full range of floods rather than a specific design event, and need time varying information across a whole event rather than just the peak of the event. Managing flood risk involves a range of different groups with different information needs AEMI (2013).

5.5.1.1. Analysis of Historic Flood Events

Managing flood risk to the community generally requires more knowledge than can be gained from historic flood events. The information available on historic flood events is generally incomplete and is unlikely to represent the full range of potential flood events. In addition, it is likely that there have been changes within the floodplain or catchment since the historic flood event occurred that would alter the behaviour or impacts of a flood of the same magnitude if it were to occur today.

The use of historic flood event information in isolation without an understanding of the potential range and severity of flood events at a location and an understanding of how this may vary within a floodplain can result in poor management decisions – leaving the community unsustainably exposed to risk.

Knowledge and experience of historic flood events provides a starting point for understanding flood risk. Modelling historic flood events can assist to:

- Calibrate and validate models against known data and the community's experience of flooding;
- Better understand historic flood events by filling in gaps in our knowledge of flood behaviour and its variation along a watercourse and across the floodplain; and
- Understand the probability of floods of the scale of historic flood events being exceeded in future.

The consequences of historic flood events can also provide valuable information for understanding flood risk. An appropriately calibrated and validated model can provide a sound basis for updating of the model to current conditions in light of changes in the catchment and floodplain since historic flood events.

5.5.1.2. Analysis of Design Flood Estimates for Current Conditions

Design flood estimates can be used for a range of purposes including:

- Understanding flood behaviour (flow paths, distribution, velocity, depth, level, timing and length of inundation) and risk and how this varies across the floodplain, over the duration of a flood event, and between flood events of different magnitudes;
- Understanding how flood behaviour, hazards and risks may change due to floodplain, catchment and climate changes;
- Establishing design standards based upon a specific design event;
- Assessing whether desired levels of service are met;
- Making decisions on the need for risk treatment, comparing and assessing treatment options, and deciding on which options to implement; and
- Designing waterway structures, basins, levees and other treatment options.

Design flood estimation for the full range of flood behaviour provides the basis for assessing the frequency and severity of flood exposure of different parts of the floodplain and the consequences of flooding to the community,providing a spatial understanding of:

- Flood extents to understand where floods of different magnitudes will impact;
- The variation in the flood functions of flow conveyance and storage within the floodplain for key events. Areas with these functions are generally areas where change in topography, vegetation or development can significantly alter flood behaviour which may lead to detrimental impacts to the existing community;
- The variation in hazard across the floodplain for key flood events (refer to Book 6, Chapter 7). This can delineate where flood behaviour in events is hazardous to people, vehicles and buildings (AEMI, 2014b); and
- The variation in flood evacuation difficulty from areas within the floodplain (AEMI, 2014c).

Outputs from design flood estimation and flood risk management processes are essential in informing government and industry through input to information systems. This can improve the accessibility of information on flood risk so it can be considered in investment and management decisions by government, industry and the community.

5.5.1.3. Analysis of the Impacts of Changing Infrastructure on Design Flood Estimates

Infrastructure crossing a floodplain can often provide some control on flood behaviour within a floodplain. Therefore the introduction of new infrastructure or modification of existing infrastructure crossing the floodplain can create or modify the flood controls within the floodplain which can influence flood behaviour and risk to the existing community.

The significance of these impacts can be assessed by altering calibrated and validated models of existing conditions to allow for changes and assessing the associated impacts. Management of impacts can lead to modifying the design of the infrastructure in consideration of its impacts upon the community or examination of ways to offset impacts upon the community.

5.5.1.4. Analysis of the Impacts of Changing Development on Design Flood Estimates

Future development within the catchment can have significant impacts on flood risk to the existing community. The impacts of development can be assessed by modifying the calibrated and validated models of existing flood behaviour to allow for changes to flow conveyance, storage and runoff conditions within the catchment.

The natural flood functions of flow conveyance and flood storage occur in flow conveyance and flood storage areas. Filling of flow conveyance areas can impact upon upstream flood levels and can result in redistribution of flows, with the potential for new flow paths being activated, affecting other areas. Filling of flood storage areas can affect both upstream and downstream flood levels.

Any decision to modify the flow conveyance and flood storage characteristics of the floodplain need careful consideration as these ramifications can be significant. The significance of these impacts can be assessed by altering calibrated and validated models of existing conditions to allow for changes and assessing the associated impacts. Management of impacts can lead to modifying the allowable changes in these areas in consideration of its impacts upon the community.

Flows at a downstream point in the catchment can also change significantly with upstream development within the catchment, even where flow conveyance and flood storage areas maintain their essential flood functions. These changes can occur due to increase in impervious areas and flow paths being shortened or having a higher proportion of impervious area. This can reduce losses leading to a higher proportion of rainfall running off and the time of concentration of flows within the catchment being reduced.

Assessment of the potential cumulative impacts of such broad changes is best undertaken in community rather than development scale flood investigations. It can provide the basis for understanding the relative significance of this change and where considered significant, assessing options to offset these impacts on a catchment basis. For example impacts on peak flood flows may, in some cases, be able to be managed using centralised or strategic scale basins or distributed (development site related) treatment measures.

5.5.1.5. Analysis of Climate Change Impacts Upon Design Flood Estimates

Climate change can have impacts on both flood producing rainfall events and on sea level and this can influence flood behaviour, frequency and impacts on the community in waterways. Assessment of the potential scale of impacts of climate change on flood producing rainfall events and its significance are discussed in Book 1, Chapter 6.

Sea level rise will directly influence ocean conditions that can influence flood behaviour in coastal waterways. Any rise in ocean conditions will directly translate to an increase in any relevant ocean boundary condition that is used in flood studies and will influence both the scale and balance of interaction of oceanic inundation with catchment flooding. Book 6, Chapter 5 provides information on the potential for coincidence of oceanic inundation and catchment or river flooding. Other guidance, such as OEH 2015 for NSW, may also be relevant and need consideration in particular jurisdictions.

The significance of these impacts of flood behaviour can be assessed by altering calibrated and validated models of existing conditions to allow for changes in flood producing rainfall events and the coincidence of oceanic inundation. Understanding these impacts can lead to an understanding of where they occur and whether management may be necessary. Management may involve strategies to allow for changes upfront or strategies that allow for adaptation over time.

Climate change may also have influence on the effective service life of infrastructure. This is discussed in Book 1, Chapter 5, Section 9.

5.5.2. Using Design Flood Estimation to Support Management of Future Development

Flood risk to future development is primarily managed by incorporating consideration of flood risk and the associated constraints (Book 1, Chapter 5, Section 5) into strategic planning and the relevant land use planning system.

Land use planning systems often use a flood standard as a basis for many flood related controls and decisions. These systems may also consider changes in climate and the influence development within the catchment will have on flood behaviour. These considerations are often made in addition to existing conditions to provide an understanding of how changes may impact upon flood behaviour and the existing community.

Systems may also require consideration of larger or extreme flood events to examine whether additional development constraints are necessary to deal with residual risks to the new development, particularly risk to life.

As new development on the floodplain can impact upon flood behaviour and the flood risk faced by the existing community, land use planning systems generally require these impacts to be assessed and managed.

Developing on the floodplain places the new development and its occupants at risk from flooding. These issues need to be considered in setting strategic directions for the community and determining development constraints.

Design flood estimation provides essential information for understanding constraints (see Book 1, Chapter 5, Section 5) that need consideration in setting strategic land use planning directions for the community, including:

- Information to inform decisions on where to (and where not to) develop and the limits on what type of development to place in different areas of the floodplain. For example, development within a flow conveyance area may have significant impacts upon flood behaviour or cause significant damage to structures. Development in this area should be restricted to enable the flow conveyance area to perform its natural flood function. A further example, such as an area with evacuation issues that is classified as flooded, isolated and submerged (AEMI, 2014b) would not necessarily be an appropriate area for a development whose occupants may be vulnerable in emergency response and therefore difficult to evacuate e.g. aged care facilities or a hospital;

- The assessment of the cumulative impacts of development within the catchment and floodplain on flood flows and behaviour. For example, the assessment of the cumulative impacts of development of the catchment can enable the examination of catchment scale solutions to offset the impacts of development on flood flows in an efficient manner. Such solutions may include a single series of basins whose interaction is considered (see Book 1, Chapter 5, Section 8); and

- Information to inform the derivation and implementation of development constraints that reduce the residual flood risk to the new development and its occupants to an acceptable level.

Design flood estimation also provides essential information to inform consideration of individual development proposals through the planning system. Studies undertaken for specific developments generally aim to assess whether the development will have significant impacts upon existing flood behaviour and the flood risk of the existing community and the impacts of flooding on the proposed development site and the residual risks to the development and its occupants.

For individual development proposals design flood estimation can advise on the:

- Suitability of the specific location for development;
- Suitability of the proposed development for the location;
- Limits on the scale of development to limit impacts on the existing community; and
- Development conditions necessary to manage residual risk to the new development and its occupants and any impacts of the development upon the existing community.

Site specific studies do not generally provide advice for setting strategic land use direction of the community.

5.5.2.1. How Can More Information Aid in Decision Making?

Having more information on flood behaviour and on flood related constraints can support informed decision making. The example provided below in Figure 1.5.3 and Figure 1.5.7 provides an example of how additional information on flood behaviour and factors that influence the risk to people and property can provide a better understanding of flood constraints so these can be considered in investment and development decisions.

Figure 1.5.3 shows the area affected by the design flood event used to set design standards for developments in the area. It does not provide any breakdown of the floodplain to highlight the varying flood function within this area, the varying degrees of hazard; or the differences in emergency response classification within the floodplain. Nor does it provide information on more frequent or more extreme floods. It therefore provides limited information for effective management.

Using the information from Figure 1.5.3 alone, Locations A, B, C and D appear to be exposed to the same degree of risk. The availability of this limited information would, most likely, result in the same development restrictions being applied to each location.

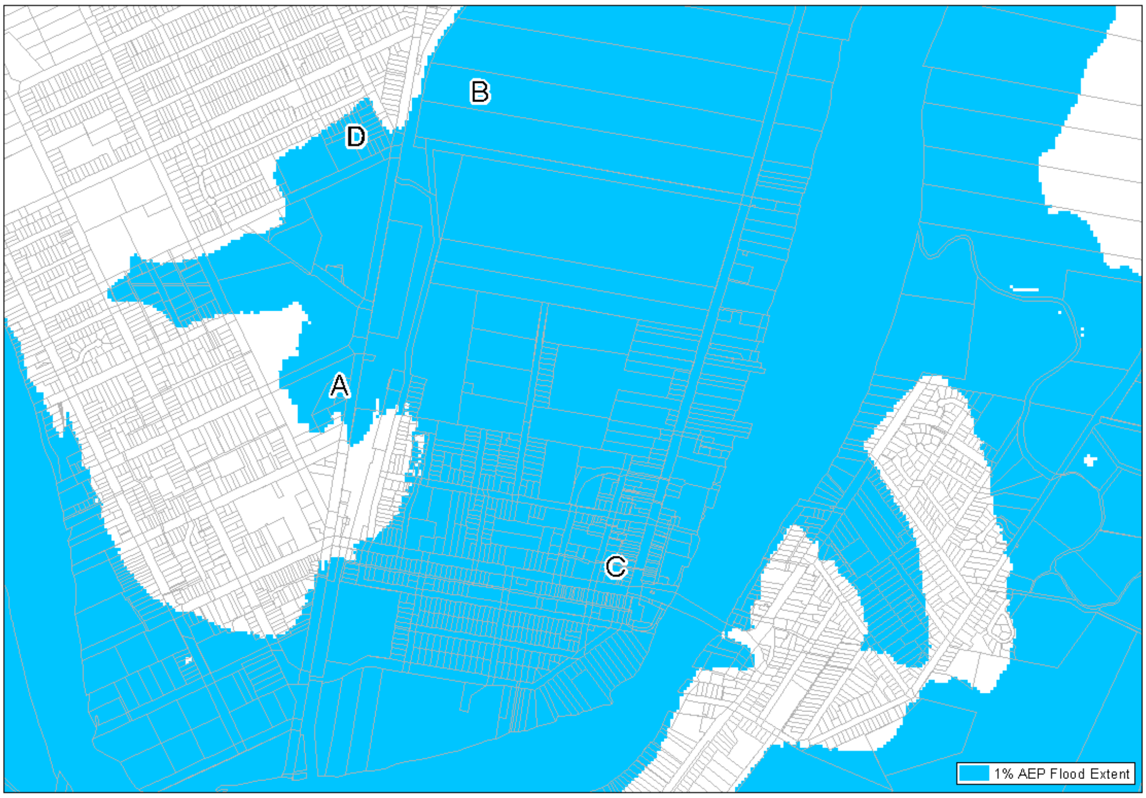


Figure 1.5.3. Map of Flood Extents

However, Figure 1.5.4 to Figure 1.5.6 shows the same floodplain but with information on how flood hazard, flood function and the flood emergency response classification varies across the floodplain. This information shows the flood situations impacting upon Locations A to D to be different and may require different management treatments.

- Location A is easy to evacuate and outside the impacts of flood function and flood conditions are not hazardous to buildings;
- Location B is in a flow conveyance area and development may impact upon flood behaviour and the flood risk of others in the community;
- Location C is isolated and completed inundated by larger floods and has a more difficult flood evacuation situation; and
- Location D is similar to Location A but is an area where floods may be hazardous to houses and people.

If these additional risk factors are considered in setting development constraints flood risk at a location can more effectively be managed at the different locations reducing the residual risks remaining. Mapping the constraints from Figure 1.5.4 to Figure 1.5.6 can provide more clarity on where to apply different development controls as shown in Figure 1.5.7.

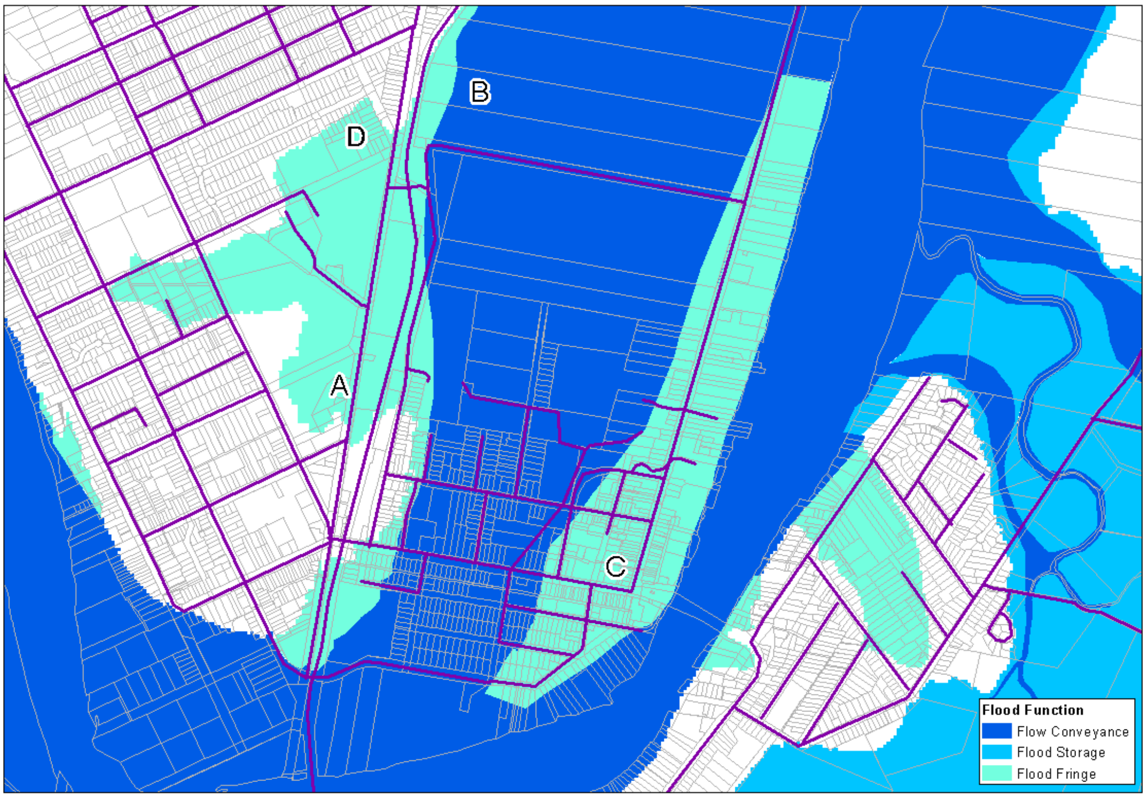


Figure 1.5.4. Map of Flood Extents and Flood Function

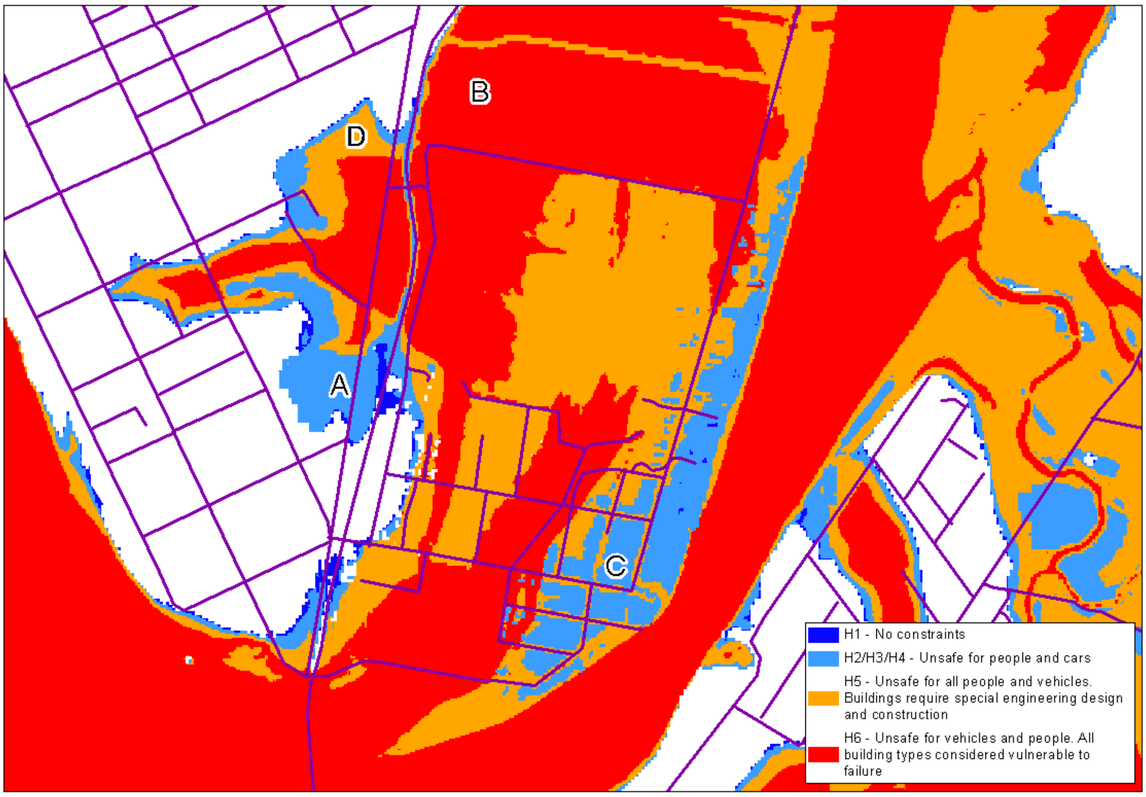


Figure 1.5.5. Map of Flood Extents and Flood Hazard

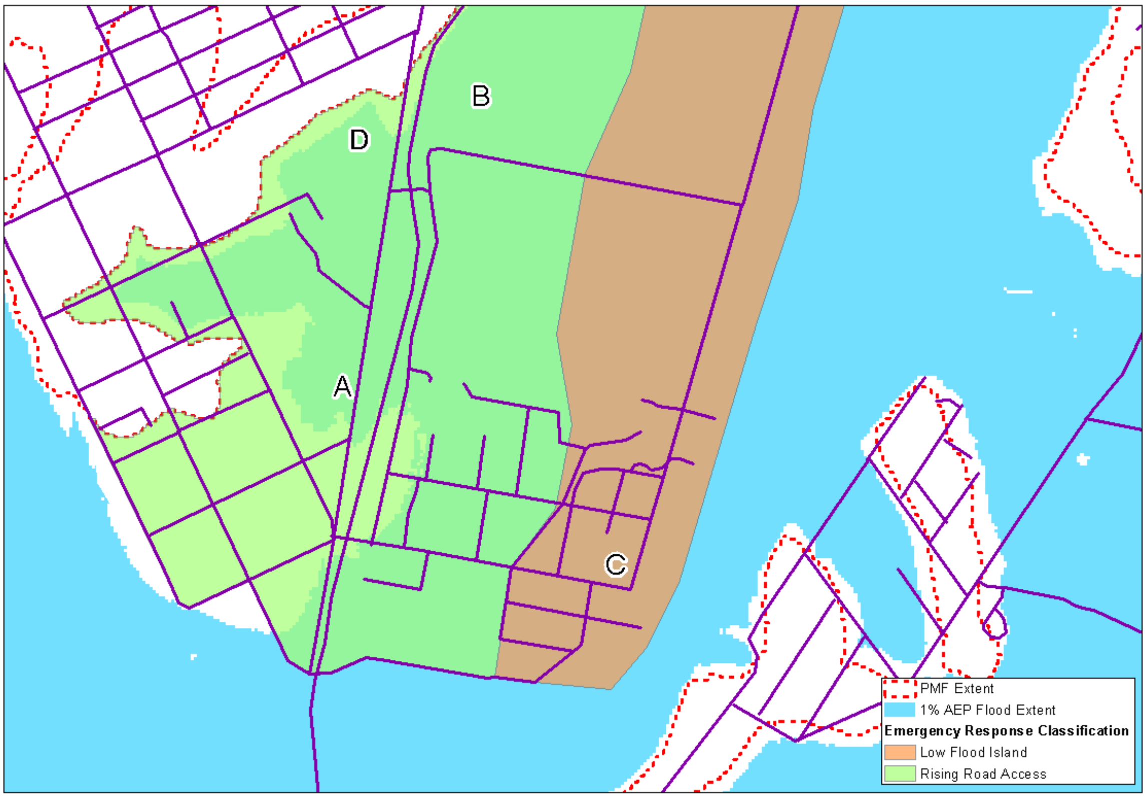


Figure 1.5.6. Map of Flood Extents and Flood Emergency Response Classification

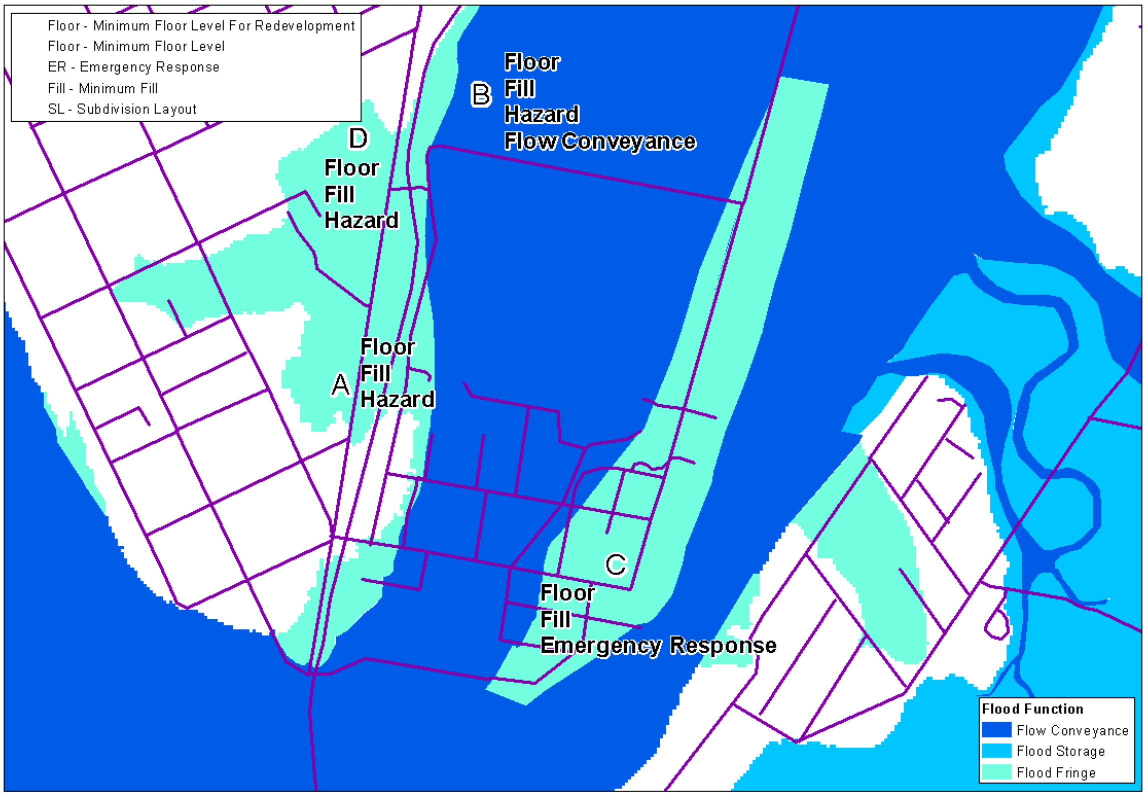


Figure 1.5.7. Map of Variation in Constraints Across the Floodplain

The additional information provided in Figure 1.5.4 to Figure 1.5.7 identifies additional risk factors in different locations without which:

- The need to consider these additional risk factors in decision making may not be evident; and
- Where it has otherwise been recognised that these additional risk factors may need to be considered in decision making it is likely that any associated constraints would be applied broadly across the floodplain. This would require studies for individual developments to determine and address these risk factors.

The additional information provided in Figure 1.5.4 to Figure 1.5.7 has the added benefit of enabling the provision of improved clarity for development conditions by enabling these to be more effectively inform land use planning systems. McLuckie et al. (2016) discusses the extension of this work as part of the development of best practice guidance on flood information to support land use planning being developed by the National Flood Risk Advisory Group and expected to be releases in the second half of 2016.

5.5.3. Understanding and Treating Risk to the Existing Community

In some cases the consequences of flooding and the associated risks may warrant changes to the existing treatment of flood risk in a community to reduce the residual risks to a more acceptable level. In other cases existing treatment of risk may be considered adequate for this purpose.

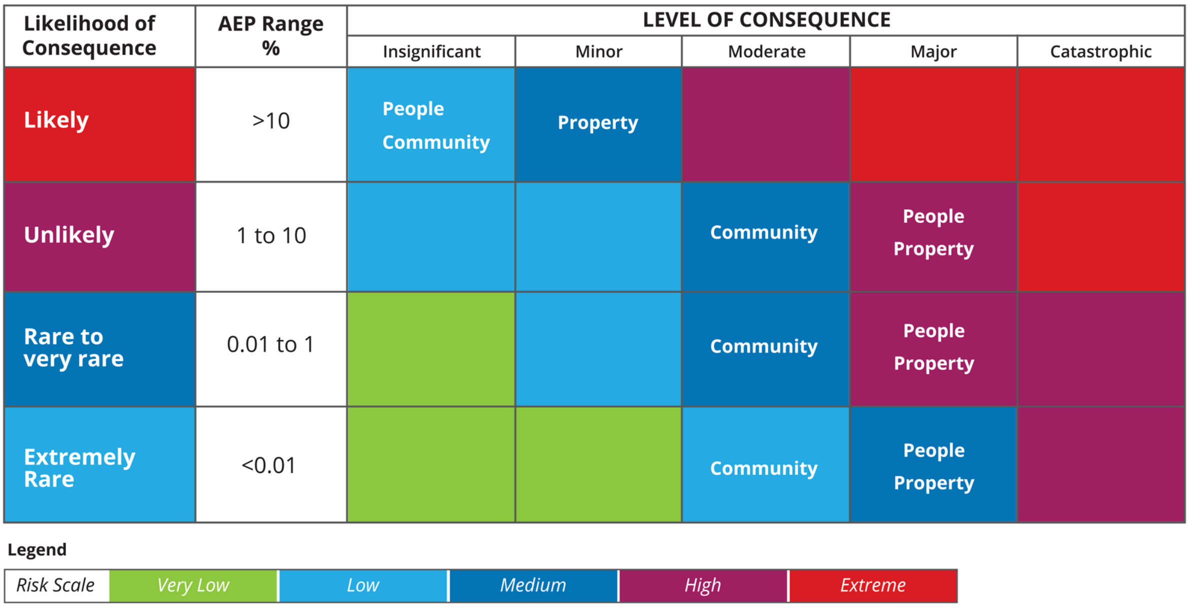
Design flood estimation can provide the understanding of flood behaviour, and the drivers for this behaviour, across a range of flood events to support management of the flood risk. It can be combined with other information to:

- Assess the consequences of flooding on the community and the natural and built environment. One quantitative measure of consequences is the estimation of flood damages. This section provides an example of the use of flood damage estimation in flood risk management;
- Assess the impacts of floods on community infrastructure such as electricity, water supply, the sewerage system, medical facilities and emergency management infrastructure (evacuation routes and centres), and provide information to consider in recovery planning for the community; and
- Examine the effectiveness of treatment options to reduce this risk where warranted.

5.5.3.1. Estimation of the Current Risk to a Community

Figure 1.5.8 provides an example of a graphical representation of the variation of risk to the different elements (people, community, property) over the full range of flood behaviour for a particular floodplain. This can involve both qualitative and quantitative estimates of consequences for different flood events to determine risk levels using the example risk matrix provided in Table 1.5.1.

In this example, for events more frequent than a 10% AEP event the consequences to people, and the community are insignificant and therefore risks are low. However, the consequences for property are minor and therefore risk is medium. Consequences to people are major for floods rarer than the 10% AEP flood event. Consequences to property rise to major in unlikely, rare, very rare events and extremely rare floods. Impacts upon the community and its supporting infrastructure are moderate for events greater than the 10% AEP and do not reach major levels.



Likelihood of Consequence	AEP Range %	LEVEL OF CONSEQUENCE				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likely	>10	**People** **Community**	**Property**			
Unlikely	1 to 10			**Community**	**People** **Property**	
Rare to very rare	0.01 to 1			**Community**	**People** **Property**	
Extremely Rare	<0.01			**Community**	**People** **Property**	

Legend

Risk Scale	Very Low	Low	Medium	High	Extreme

Figure 1.5.8. Example of Estimated Average Risk to a Community Due to Flooding

Figure 1.5.8 shows the risks to people and property for events between a 10% and 0.01% AEP event. The risk to the community is low except in floods between a 10% and 0.01% AEP event where they are medium.

5.5.3.2. Estimating Flood Damages to an Existing Community

One of the ways to quantitatively assess impacts to the community is to estimate flood damages. This generally involves an aggregation of estimates of flood damages on individual properties considering both direct costs (damages to structures and their content) and indirect costs (such as clean-up and disposal or materials, loss of earnings, sales and production, temporary relocation expenses) and an allowance for or estimate of infrastructure damages. However, it is important to note that this typically does not incorporate all risk factors, such as risk to life, and these additional risk factors may need to be accounted for through a qualitative assessment.

A range of methods are used to derive damages for individual properties. These include:

- *Rapid assessment techniques* - which rely on flood extents to determine the number of properties of different development types (residential, commercial and industrial) affected and apply a fixed damage per property.

- *Techniques based upon the use of stage damage curves* - for different development types and in some cases styles and sizes of buildings (an example for residential buildings derived from DECC (2007) is provided in Figure 1.5.9). This technique provides for variation in damage to structures and yards and their contents with depth above ground level and structure floor level. Approaches, such as this allow for the use of representative buildings within the floodplain. Whereas other approaches may require the style and size of houses to be determined and individual buildings to be considered in more detail.

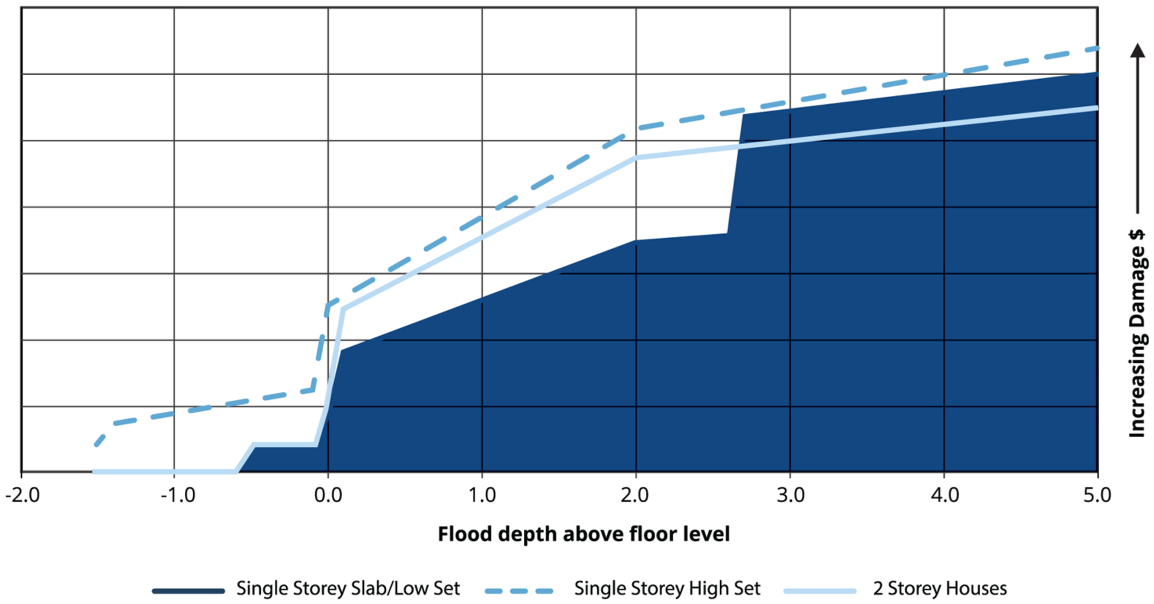


Figure 1.5.9. Indicative Stage Damage Curve for some Residential House Types

Note: There are many different stage damage curve relationships for residential development. Different damage relationships also exist for different types of development (e.g. commercial and industrial). These may be determined based upon the use of historical damage, insured loss information or based upon building component damage at different depths. However, no definitive set of curves exist and work in this area continues to evolve. Commercial and industrial damages can be very complex given the changing nature of the occupation of individual sites. The damage to the structure of the building will not generally change significantly with use but the contents damage can vary significantly. For example, the same light industrial storage area could house aluminium cans for recycling or computer components for assembly and therefore the damages to contents due to flooding would vary greatly.

Assessment based upon stage damage curves requires information on flood extents to determine which properties are affected and flood levels. This information can be used with location, ground level and structure floor level information (determined using survey or approximation methods) to estimate damages at an individual site. These can then be aggregated to estimate damages to a community or area.

Figure 1.5.10 provides an example of an aggregated flood damage curve across the full range of flood events for a community. This provides a quantitative understanding of the impacts of flooding upon the community and the built environment. It can also provide a baseline for considering the benefits of management options or infrastructure projects. Each point on the flood damage curve has a probability of exceedance in any given year. Examining this curve shows that there is no damage in a 20% AEP event with damage in the 0.5% AEP event being approximately $20 Million.

To use this information for flood risk management, particularly when examining the benefits of management measures, this information needs to be translated into an Annual Average Damage (AAD). This is achieved by determining the area under the curve. Book 1, Chapter 5, Section 12 provides an example of calculation of Annual Average Damages based upon the flood damage curve in Figure 1.5.10.

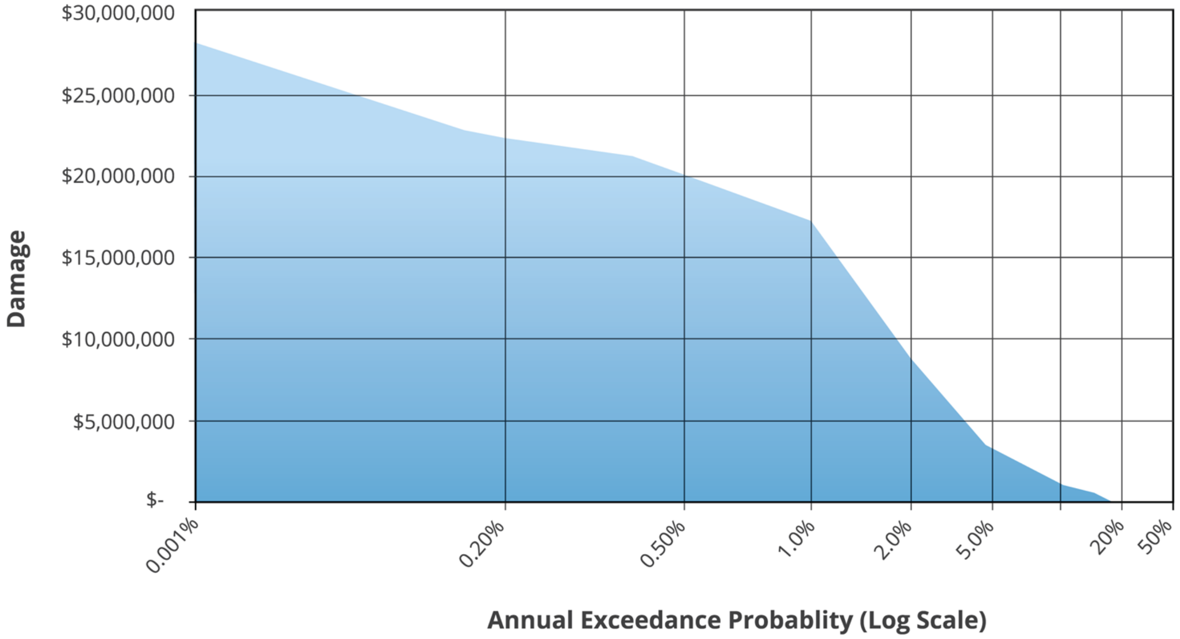


Figure 1.5.10. Example of Flood Damage Curve for a Range of AEP Flood Events

5.5.3.3. Assessing Options to Treat Flood Risk

Where treatment options are proposed that may change flood behaviour the calibrated and validated models that define the existing flood situation need to be altered to incorporate proposed treatment options and design flood estimates developed for the changed conditions.

Comparing this information to the existing flood situation can indicate changes in flood behaviour, and in combination with other information, changes in the consequences of flooding on the community. Flood extents, flood function, flood hazard and emergency response classification and damages may alter for specific areas and different design flood events. Where changes in behaviour are significant there are likely to be areas where flood impacts are reduced and other areas where they may be increased. These changes in consequence can be used to assess the benefits and costs to the community and the limitations of the treatment option.

Section 9.4 and Table 9.3 of AEMI (2013) outline some of the issues that should be considered when selecting and comparing treatment options. The benefits and costs of treatment options may be assessed singularly as well as in combination with complimentary measures as it is rare for a single treatment option used in isolation to effectively manage flood risk to a community. For example, a levee may be built to reduce flood damage in a town in combination with a flood warning system to provide additional warning and upgraded evacuation routes to improve community safety during floods.

One quantitative way of determining the financial efficiency of the project involves understanding the benefits in reduction in flood damages and comparing this to the costs of achieving and maintaining this benefit. A reduction in flood damages can be assessed by determining the reduction in Annual Average Damages and exposure of the community to flooding with treatment options in place. For example the use of minimum floor levels based upon the 1% AEP flood for new development, or a levee designed to exclude a 1% AEP flood from an existing flood affected area will reduce flood damages for events up to but not exceeding the design flood event (in this case 1% AEP event). However, the consequences of floods rarer than the design floods may not change significantly and there may still be substantial impacts upon the community.

Annual Average Damages calculated across the full range of flood events provides a sound basis for understanding the financial benefits and limitations of the project so this can be considered in decision making and enables the calculation of Annual Average Benefits.

Figure 1.5.11 provides an example of the estimation of the financial benefits of a treatment option. It shows the damage curve for the same flood situation as shown in Figure 1.5.10 but both without any treatment and with a treatment option in place.

In this example the treatment option is a levee. The aim of the levee is to reduce flood damages and the frequency of community exposure to flooding and associated risks for events up to the design flood event, in this case the 1% AEP event. Whilst there are some benefits for rarer floods these can be seen to diminish quickly in rarer events. In a 0.2% AEP event the damages with and without the treatment options would be the same.

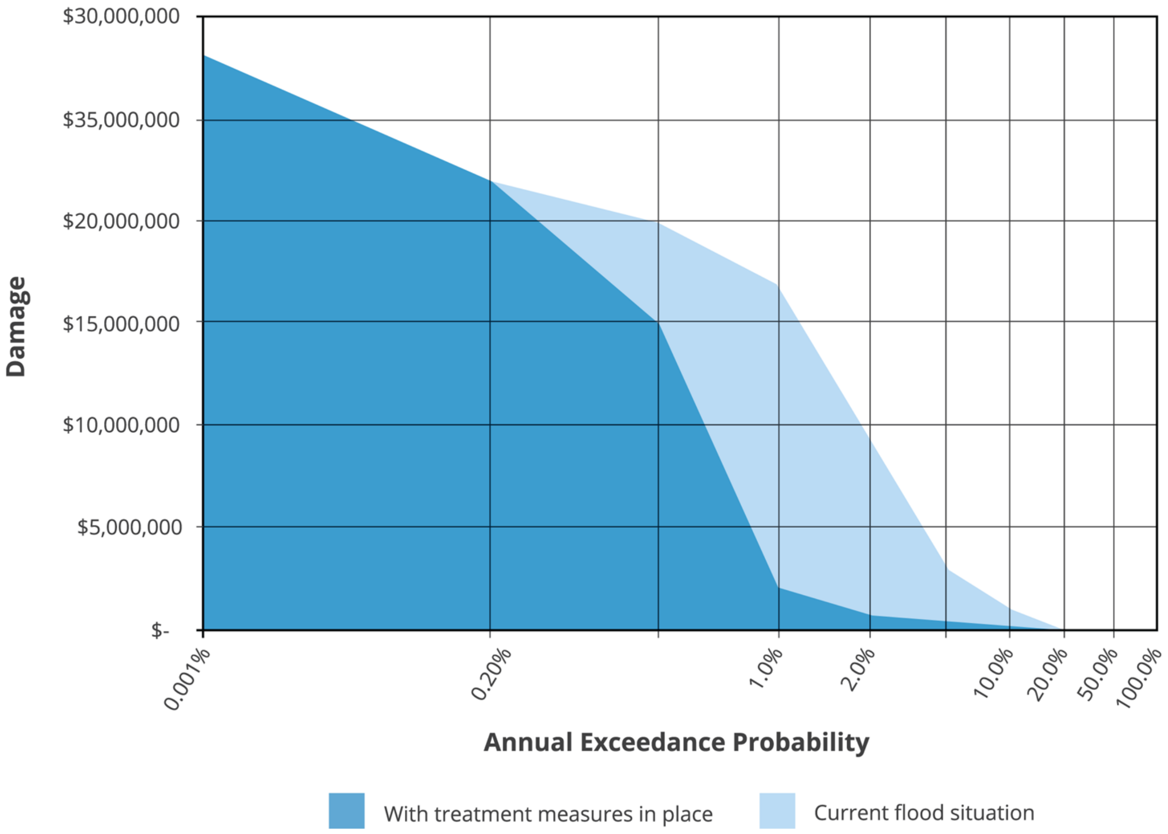


Figure 1.5.11. Example of Flood Damage With and Without Treatment Options for a Range of AEP Flood Events

The reduction in Average Annual Damages (AAD) or the Average Annual Benefit (AAB) can be used to determine the net present value of the benefits. An example is provided in Book 1, Chapter 5, Section 12.

This can then be compared with the Net Present Value (NPV) of life cycle costs of the treatment options to determine the Benefit Cost Ratio (BCR), which provides a measure of the financial efficiency of the project. Book 1, Chapter 5, Section 12 provides an example of estimation of Net Present Value of life cycle costs.

Book 1, Chapter 5, Section 12 provides an example of estimation of the Benefit Cost Ratio. Lifecycle costs and lifecycle benefits for individual years are shown in Figure 1.5.12. Figure 1.5.13 shows the same figures altered under current day dollars assuming a 7% discount rate.

The Benefit Cost Ratio calculated can be used in conjunction with consideration of other benefits, such as reduction in risk to life, reduction in the impacts upon community function and infrastructure and with similar information for other treatment options (including those providing protection for different AEP events) to inform decisions on managing risk.

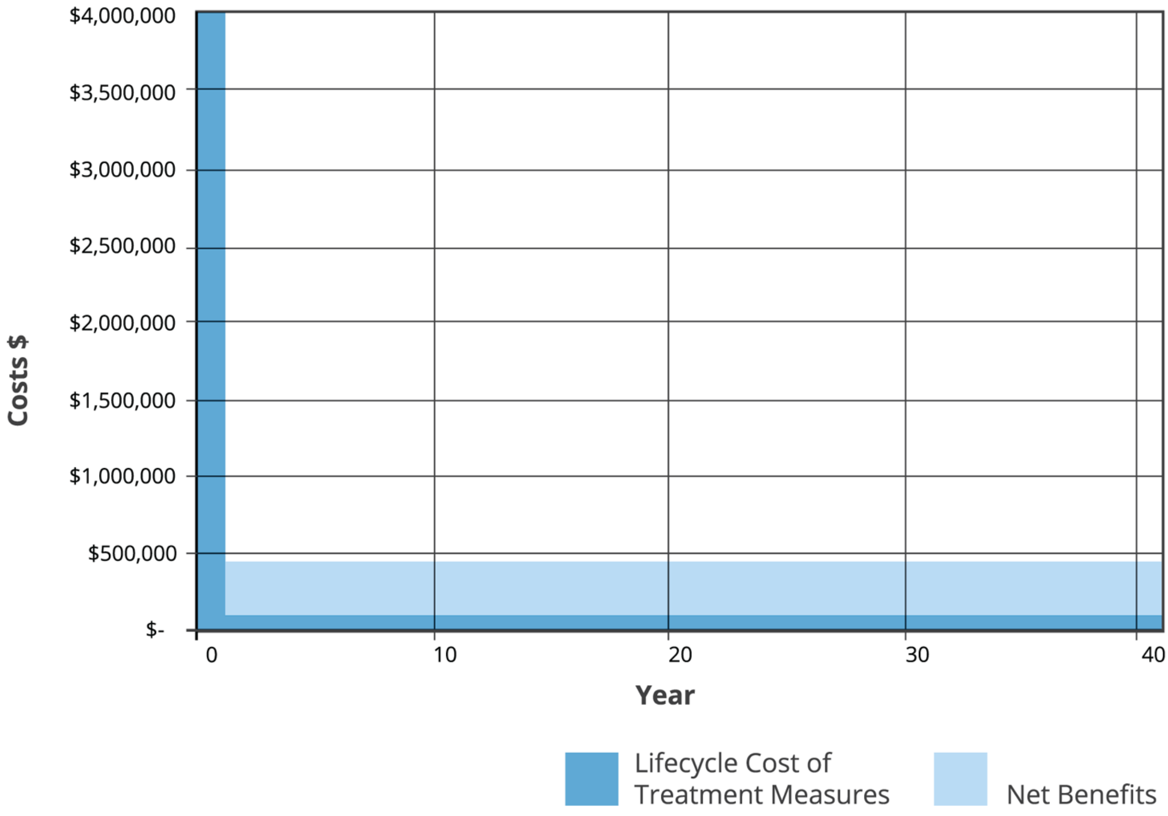


Figure 1.5.12. Example of Annual Lifecycle Benefits and Costs

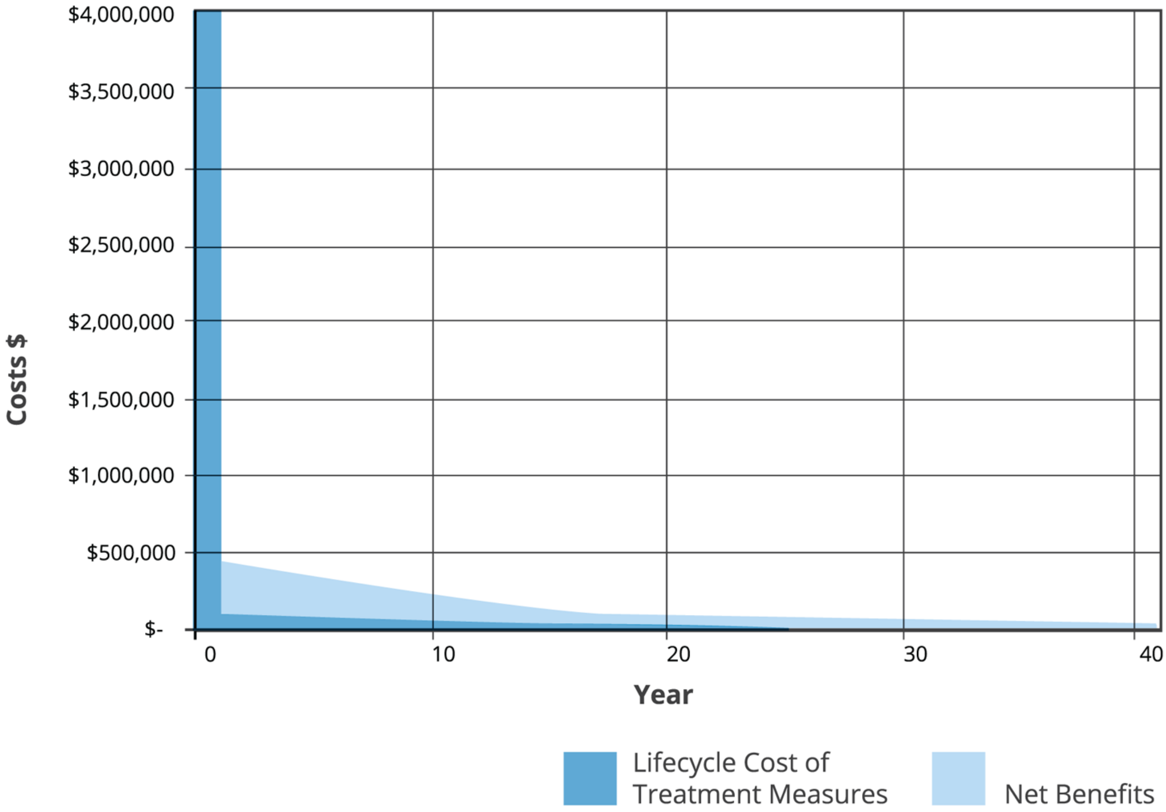
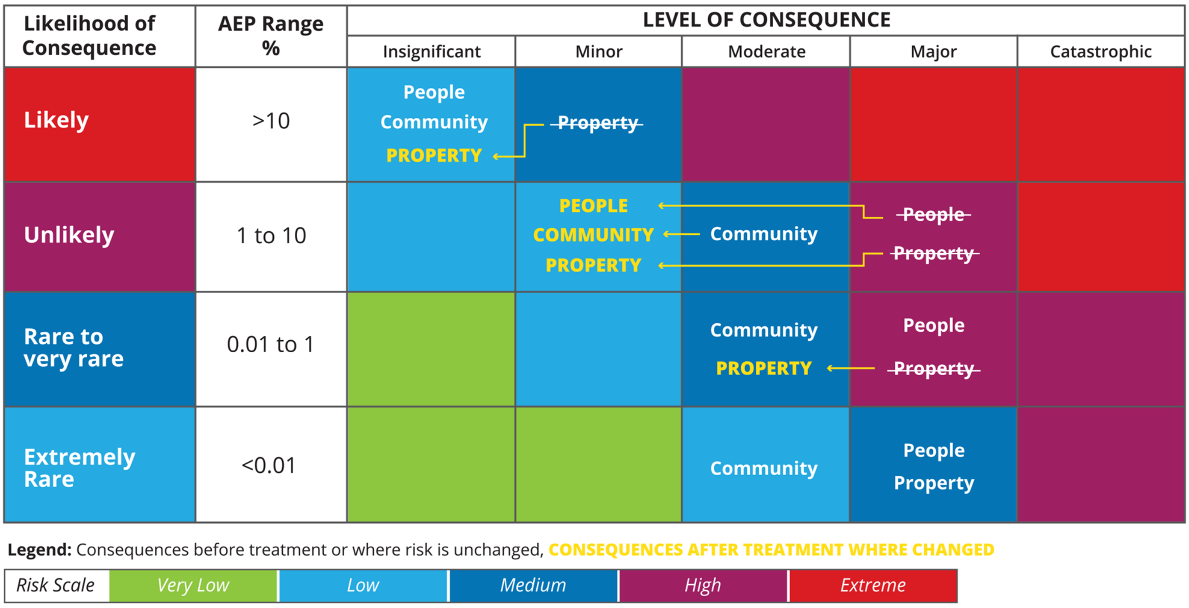


Figure 1.5.13. Example of Lifecycle Benefits and Costs Adjusted to Todays $ Using a 7% Discount Rate

Figure 1.5.14 re-examines the risks identified in Figure 1.5.8 to highlight how these have changed through the implementation of treatment options to provide protection for the 1% AEP event. This example shows a reduction in risk to property from a maximum of high to a maximum of medium in events above a 1% AEP event but low in events less than the design event.

However, risk to people is still high due to the impacts of events greater than the 1% AEP event. This may warrant additional treatment options being considered which, depending upon why this risk remains high, may include flood warning systems, improved emergency management planning and improvements to evacuation routes.

Note: there is no change to the risks in extreme events. The risk to property has been reduced in rare events due to the reduction in damages as a result of risk management measures.



Likelihood of Consequence	AEP Range %	LEVEL OF CONSEQUENCE				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likely	>10	People Community PROPERTY	~~Property~~			
Unlikely	1 to 10		PEOPLE COMMUNITY PROPERTY	Community	~~People~~ ~~Property~~	
Rare to very rare	0.01 to 1			Community PROPERTY	People ~~Property~~	
Extremely Rare	<0.01			Community	People Property	

Legend: Consequences before treatment or where risk is unchanged, CONSEQUENCES AFTER TREATMENT WHERE CHANGED

Risk Scale	Very Low	Low	Medium	High	Extreme

Figure 1.5.14. Example of Estimating Changing Average Risk to a Community Due to Flooding with Instigation of a Treatment Option

5.6. Managing Flood Risks to Mining, Agricultural and Infrastructure Projects

As well as considering flood risks for existing and future development within communities as discussed above, the interaction of mining, agricultural and infrastructure (particularly linear above ground infrastructure such as road and rail embankments and levees) require management. Where located in the floodplain, these developments are:

- Susceptible to flood risk; and
- May impact upon flood behaviour with detrimental impact to others in the community.

In many cases, a design flood standard may not be available or appropriate, and a risk management approach as described in Book 1, Chapter 5, Section 4 may need to be undertaken. A general overview of some of the issues to be considered are included in Book 1, Chapter 5, Section 6 to Book 1, Chapter 5, Section 6.

Some of these projects or related projects with building of infrastructure can be considered short term projects due to their short term exposure to risk. Assessment of the risks associated with short term projects is discussed in Book 1, Chapter 5, Section 6.

In the same way that short term projects need special consideration, potential changes over the effective service life may need to be considered specifically for longer term infrastructure. Effective service life is discussed in Book 1, Chapter 5, Section 9, while potential implications of changes over the life of the project are discussed in Book 1, Chapter 5, Section 10.

5.6.1. Mines

Mines developed in the floodplain may require levees or similar flood mitigation measures. These levees need to be designed to an appropriate level of flood immunity and may also have an impact on flood levels outside the levee. The risk and potential damage caused by flood inundation both inside and outside the mine needs to be analysed, with a similar process to that used for community development discussed in Book 1, Chapter 5, Section 5.

There are usually key issues of concern for the mine:

- Risks associated with inundation of the mine and its operations. The risk for mining may be from flooding of the mine pit, emplacements, infrastructure, machinery or underground workings, which may disrupt production, damage equipment and result in a risk to life; and

- Risks associated with changes to flood behaviour for communities upstream or downstream. The risk may be associated with changes in flood behaviour, potential significant erosion and sedimentation deposits, polluted water from tailings dams etc.

The key difference between the two elements is that there will generally be two distinct groups of stakeholders in the risk assessment. These different stakeholders may have different risk profiles and this will need to be considered as a part of the assessment. Risks associated with the inundation of the mine will be typically be associated with the mining company, which may also incorporate workers' unions and insurance companies. Risks associated with the community may be associated with government, the local community, community interest and environmental groups.

As a result of these different stakeholders, the risks and associated risk profiles may need to be considered separately. There is also unlikely to be specific design flood standards associated with inundation of the mine, as it may be more driven by acceptable closure periods etc. Therefore, a full risk assessment (Book 1, Chapter 5, Section 4) may be required to derive appropriate management measures.

5.6.2. Agriculture

Flooding in agricultural regions can have concerns for crops, livestock and infrastructure. Crops may be damaged by inundation either: directly by floodwaters; or due to the extended period of inundation (where crops may be susceptible to longer term rather than short term inundation). Livestock may be lost if unable to be relocated to areas outside flood limits.

In order to determine appropriate risk mitigation measures for agriculture, the specific implications for livestock and crops need to be considered, and the risk assessment will need to incorporate these factors. In addition, agricultural infrastructure such as irrigation pipes, fences, buildings and machinery may be damaged and these can have significant value. Book 1, Chapter 5, Section 4 provides guidance on determining appropriate mitigation measures incorporating some of these different factors.

In some areas of high value agriculture, the farm land may be protected by levees (or other infrastructure) and these have similar issues to levees built for other flood mitigation purposes. The appropriate protection level of these infrastructure would be based on a risk assessment considering the above factors, as well as potential impacts to the community upstream and downstream.

The key stakeholder groups for undertaking a risk assessment may include:

- The farming operation(s) who will be directly impacted by the flooding; and

- Community both upstream and downstream, who may be represented by local government, community interest groups, environmental groups etc.

5.6.3. Road and Rail Projects

Road and rail embankments are built across floodplains in many situations. To ensure a suitable level of flood immunity, the infrastructure will be built on embankments which will usually cross watercourses. In this case, the infrastructure must be designed to ensure a suitable level of service (ie. considering the acceptable degree of disruption to transport services for the route), as well as withstand an acceptable risk of damage from scour, submergence, or overtopping of structures. The consideration of disruption to transport depends not only on the frequency of closure, or flood immunity, but also on the duration of closures, both during large floods and as an annual aggregate.

It also needs to consider the intended function of a road during a flood event, particularly where it has an important role in community evacuation or recovery plans. Design of embankments associated with these structures requires analysis of the road or rail level as well as the sizes, locations and types waterway openings. This is to ensure an acceptable level of flood immunity, duration of closure and damage from floods as well as an acceptable impact on upstream flood levels. Discussion of flood assessment and flood risk for road and rail projects can be found in the Austroads Guide to Road Design – Part 5 (Drainage)[1].

Key stakeholders may involve:

- Relevant road authority;
- Community groups, potentially represented by local government, community interest groups etc; and
- Relevant emergency response authorities and groups.

5.6.4. Short Term Projects

Short term or temporary projects are those that will only have a limited effective service life (refer Book 1, Chapter 5, Section 9). Some examples might include:

- Construction projects. For example, a coffer dam protecting an excavated area for a period of 6 months;
- A planned festival or community event in the floodplain, which occurs over a 2 day period; and
- Short term mining operations. For example, a levee to protect a portion of a quarry for a period of 3 months.

With short term projects, it is particularly important to understand the likelihood component of the risk assessment as well as the effective service life (refer Book 1, Chapter 5, Section 9).

Flood design standards are typically developed for long term projects and are based on an assumed effective service life that is generally many years. For example, a residential house might have an effective service life of 50 years. Therefore, when a 1% AEP design flood standard is adopted for the floor level, for example, that is equivalent to an approximate 39% chance that the floor level will be exceeded during the effective service life (using a SLEP terminology, as identified in Book 1, Chapter 5, Section 4).

However, if a 1% AEP flood design level is adopted for a coffer dam for excavation for an effective service life of 6 months (ie. a 6 month construction period), then the chance that it

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[1] http://www.austroads.com.au/road-construction/road-design/resources/guide-to-road-design

will be exceeded will be roughly 0.5% during its service life. Therefore, assuming that the consequences remain the same, then the risk profile is significantly more conservative. If a 39% chance of exceedance during its effective service life was assumed to be more appropriate, then that would be equivalent to somewhere between a 50% and a 100% AEP event.

Therefore, a SLEP approach to flood design standards and flood levels can be more readily understandable for short term infrastructure.

However, a full risk assessment will typically be required to understand all the likelihoods and consequences and therefore the risks. For example, the risk to life for a coffer dam may be significant where sufficient warning is not available.

5.7. Managing Flood Risks in Relation to Dams

The guidelines relevant to dam safety is provided by ANCOLD (2003). These guidelines provide an over-arching framework that integrates risk assessment with traditional standards-based engineering practice. They provide guidance on the generic steps involved in undertaking risk assessment for dams, and these are updated periodically with changing understanding and practice.

The dams industry has used risk assessment over the past two decades as a valuable means to establish upgrade priorities and justify the urgency of completing dam safety actions in a transparent and rational manner. However, the national ANCOLD guidelines only support risk assessment as an enhancement to traditional standards-based solutions for important and conclusive decision making. The guidelines are currently being revised, and it is likely that there will be an increased focus on the use of risk-based criteria for final decision making in accordance with changing practice (for example, NSW Dam Safety Committee, 2006).

One of the key differences between dam safety management and floodplain management is the probability domain of interest: the scale and nature of life safety risks posed by dams are generally considerably greater than encountered in floodplain management. The tolerable risks associated with these potential consequences are three to four orders of magnitude rarer than those associated with natural floods. The concept of annualising a high consequence risk based on a 10^{-6} loading condition is mathematically straightforward, but such analyses are not easily combined with more common risks and have little practical utility.

Accordingly, risk assessment for dam safety is focussed on reducing the risks to life (and property) to as low a level as reasonably practicable. It is unusual for dam safety decisions to be governed by the need to balance the costs of upgrading works against damages avoided, and more typically such decisions are dominated by life-safety considerations.

The most relevant guidance on dam safety in this document is provided in Book 8. This provides guidance on the procedures most relevant to the extreme flood risks of interest. It also includes procedures relevant to estimation of the Probable Maximum Flood, which represents the upper limiting magnitude of flood is relevant to standards-based decision making.

5.8. Managing Flood Risks using Basins

Basins can have an important role in reducing downstream flood flows and associated flood risks to the community. They may be built to manage existing community flood problems or to offset the impacts of upstream development on downstream flood risk. A basin may be used in isolation or as part of a series of basins within a catchment to reduce peak design flood flows and risks for the design event(s) at key downstream locations. The design performance requirement is therefore generally either:

- To reduce peak flows for a certain design event(s) to a certain maximum amount. For example, for a basin designed to offset the impacts of upstream new development this may be the pre-development peak downstream flow. For a basin designed to reduce downstream flood impacts this may be to reduce peak basins discharges to a level that reduces flood impacts on the downstream community to an agreed level; and
- To maximise the potential benefit of a basin at the location on downstream flood behaviour to reduce impacts on the community.

An effectively designed basin has to balance restriction of outlet capacity with having available storage capacity near the peak of a flood event. This enables the peak of flood flows to be stored and the stored volume discharged later in the event, as illustrated in the example in Figure 1.5.15.

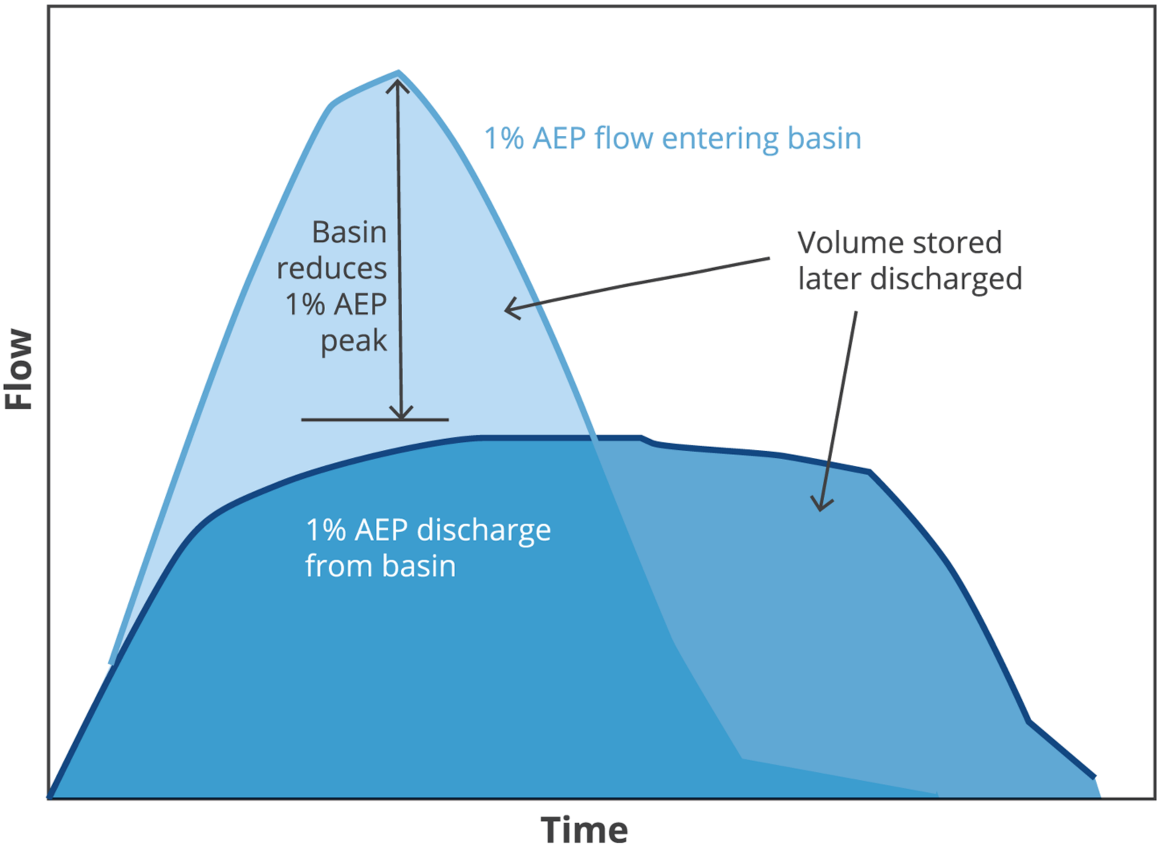

Figure 1.5.15. Example of Impacts of a Basin on Flood Flows in a Design Event

This can significantly alter the critical storm duration with the peak flood flow entering a basin likely to be derived from a shorter duration storm than the peak discharge flow from the basin. Storm pattern can also have a significant impact on basin operation and the storage volume available when the peak of flood flows arrives. For example, if the peak arrives later in the storm the available storage volume may be lower and therefore the basin may have less impact on downstream peak flows.

In addition, critical storm durations are also likely to vary with the AEP of the flood being modelled. It is not unusual for the peak basin discharge in a more frequent flood than the design event to occur in a longer duration storm event as storm volumes are lower and the basin storage will have more impact upon peak discharge. However, for events larger than the design event the opposite is true. There is likely to be less storage volume available at the storm peak so it will have less influence on peak basin discharge. Therefore the critical downstream discharge from rarer events than the design event will likely occur from shorter duration storms. For extreme events this is likely to be closer to the critical storm duration at the location without the basin.

Therefore with a basin in place the peak downstream flood flow is sensitive to both the storm duration and the storm pattern and the routing of flows through the basin. As such basin design can be particularly sensitive to both storm temporal pattern and critical storm duration.

Robust design approaches for basins that test and consider a wide range of storm durations and a range of potential variations of storm pattern for each of these storm durations are recommended for the full range of flood events. Variations in storm pattern should include testing of early, centrally and late weighted storm patterns for the same time duration to test whether the basin can meet the required design criteria with this variation.

Other key points to consider in modelling and designing detention basins include:

- *Considering the impacts of events larger than the design event* -The basin will generally be designed to reduce flood flows in a particular design event. However, in the majority of cases it is unlikely to have significant impacts on peak flows in extreme events. This can mean that there is a significantly larger difference between the extreme and design event flows entering and discharging the basin. Figure 1.5.16 provides an example. This situation is likely to result in a faster rate of rise of downstream flood levels for events larger than the design event (as these events result in high level spillway operation) than would have occurred without the basin. It is essential that this difference is understood and considered in basin and high level outlet design to manage the flood risk downstream of the basin. Residual risk downstream of the basin, including any limitations in emergency response and associated planning, needs to be considered and may require additional management measures including flood warning, community awareness, flood related development controls;

- *Upstream impacts of basins* - The construction of a basin can also have significant upstream impacts on flood behaviour and these are an important consideration in the design of a basin. This should be examined for the full range of flood events to ensure that any impacts on upstream flood risk and the management of this risk (including emergency management planning) are understood;

- *Detentions basins act as dams during flood events* - Therefore, basin design needs to consider dam safety aspects as discussed in Book 1, Chapter 5, Section 7 and Book 8; and

- *The use of multiple basins in a catchment* - Where multiple basins are designed to provide more strategic benefits, ie., away from the downstream boundary of their individual locations they should be designed on a catchment wide basis to ensure their interaction does not result in adverse impacts upon flood behaviour. Use of multiple basins in a catchment without consideration of interaction has the potential to result in adverse impacts on flood behaviour.

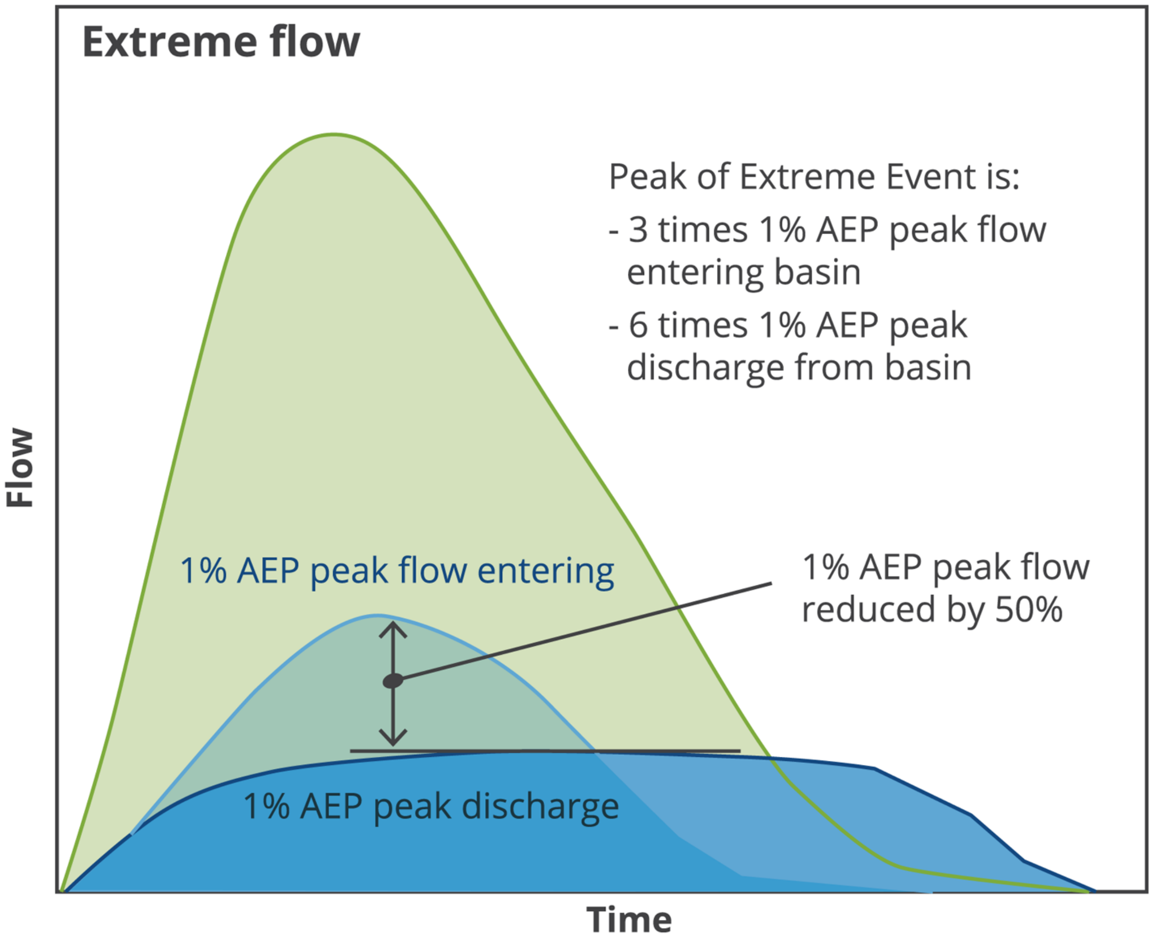

Figure 1.5.16. Example of Difference in Impacts of a Basin on Flood Flows in a Design Event Compared to an Extreme Event

5.9. Effective Service Life of Infrastructure

The longer the operational life of an infrastructure proposal is, the greater the potential for changes to occur in terms of risk, in terms of likelihood and consequences due to either changes in the catchment or floodplain or climatic changes. Typically, the duration of a proposal may be considered in terms of:

- *Economic Service Life* - The total period to the time when the asset, whilst physically able to provide a service, ceases to be the lowest cost option to satisfy the service requirement;
- *Design Service Life (DSL)* - The total period an asset has been designed to remain in use; or
- *Effective Service Life (ESL)* - The total period an asset remains in use, regardless of its Design Service Life.

Currently most guidelines are based around evaluating design service life. However, the difference between the ESL and DSL can be significant and should be recognised in risk assessment of a proposal (Figure 1.5.17).

ESL can be enhanced by factors which increase life such as maintenance, or diminished due to factors that reduce life such as significant weather events. It is considered that a proposal's ESL is of primary importance in risk assessment and should be considered in evaluating risk and setting design flood standards.

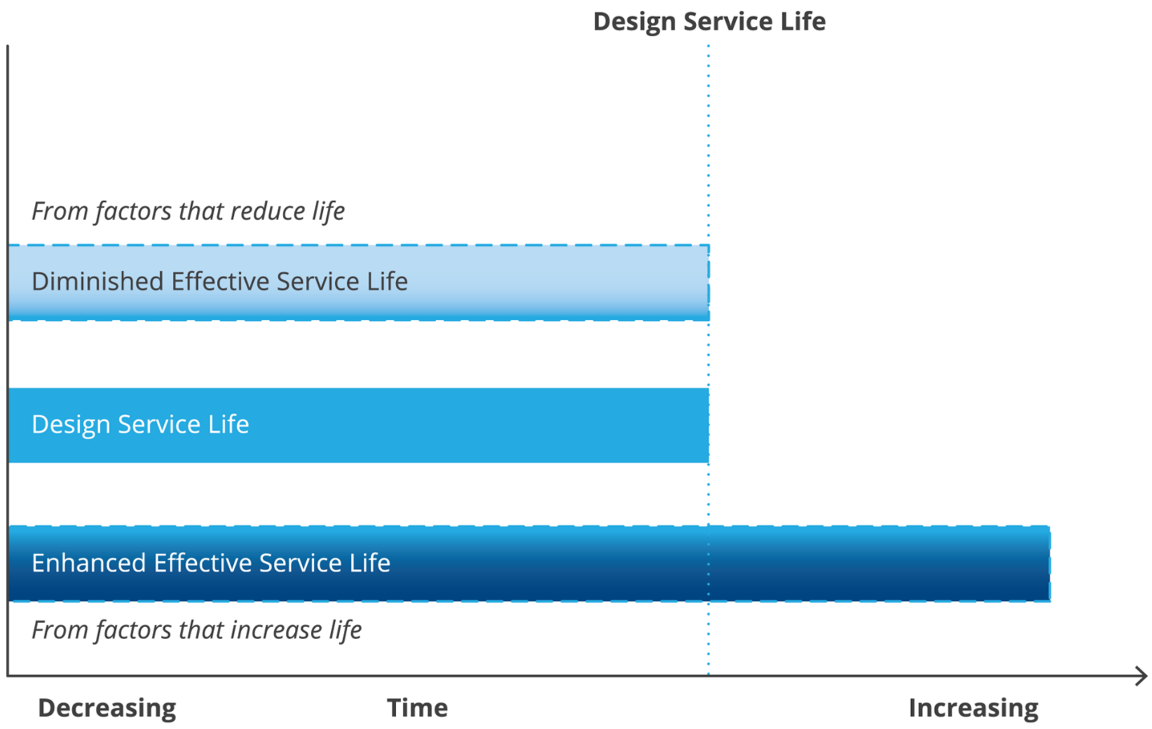

Figure 1.5.17. Design Service Life versus Effective Service Life (derived from United States Environment Protection Agency – 2007)

5.9.1. Estimating Effective Service Life

The effective service life of a particular project may be difficult to estimate. The following conditions are likely to lead to the effective service life extending past the design service life:

- *Magnitude of infrastructure* – very large infrastructure projects are more likely to remain in place longer than smaller projects (e.g. bridges, dams), due to the difficulties in replacing them;

- *High decommissioning or replacement costs* – where decommissioning or replacement costs are high there may be strong economic incentives to continue utilisation of the project (e.g. buried pipes within an urban environment); or

- *Integrated development* – where the project forms part of a broader piece of infrastructure or on-going service there may be economic incentives to continue utilisation of the project, particularly where a change to one component would require a change to others (e.g. road alignment – a road may be reconstructed/ rehabilitated over time, but due to other constraints, will not be able to be changed in terms of elevation or geometry).

Determining the effective service life of infrastructure is complex as it is a product of infrastructure design, materials, environment, maintenance and rehabilitation regime and use. For example, exposed infrastructure (e.g. roads) typically has a lower service life in tropical climates than in sub-tropical climates. Similarly, pipes that lie below a water table typically have shorter service lives than pipes that lie above a water table. The rate of degradation of construction material (e.g. metal, plastic pipes) will also vary with circumstance (e.g. saline vs non-saline conditions). Maintenance and rehabilitation of infrastructure may also seek to extend a project's expected service life (for example, a lining installed in a stormwater pipe).

Table 1.5.2 summarises some of the typical life expectancies (and range in life expectancies) for various infrastructure types. Table 1.5.2 shows that the range within and between infrastructure is high. Within Australia, data for long-lived assets is limited as the majority of the infrastructure has not yet reached its effective service life.

Table 1.5.2. Infrastructure types and potential Effective Service Life[a]

Infrastructure	Effective Service Life expectancy
Water Treatment Plants	20 - 50 years
Concrete Kerb and Gutters	40 - 70 years
Stormwater Pipes	80 - 100 years
Wastewater Systems	50 - 80 years
Residential Buildings	40 - 95 years
Roads	35 - 110 years
Commercial Buildings	15 - 150 years
Open Stormwater Channels	10 - 100 years
Locks and Weirs	40 - 200 years
Dams	50 - 500 years

[a] Data represents a synthesis and interpretation of a number of reports including: IPART (2012), Cardno (2014), USEPA (2014), International Transport Forum (2013), Tonkin (2009).

For projects which have a relatively short design / effective service life (e.g. less than five years), it may be reasonable to assume the risk profiles faced are static for the duration of the project as the likelihood or magnitude of changes to any risks may be negligible in comparison to the overall risk level. In contrast, longer life-span projects will be exposed to a higher level of non-stationary risk which could be considered in design.

5.10. Estimating Change in Risk over Time

Conditions in floodplain are not static. They vary over both in the short and long term and can affect the likelihood or the consequences of flooding. Some of these potential changes (or sources of non-stationarity) are discussed below.

“In many cases, flood studies reflect current conditions at best, and more likely past conditions since the studies often rely on old data …. …..flood risk criteria used to site and design a project should rely on conditions the location is likely to experience during the project's lifetime, not past or current conditions.” (Floodplain Regulations Committee, 2010).

5.10.1. Changes to Likelihood

The likelihood of given magnitude events occurring may change over time due to a large number of variables including:

- *Seasonality* - the seasonality can alter the statistical likelihood of flood events occurring as some events. For instance some catchments tend to have are prone to flooding associated with summer climates;

- *Climatic Variability* - Various weather patterns such as El Niño influence the likelihood of flooding. El Niño events have a life-cycle during which the impacts vary, both in terms of spatial extent and timing;

- *Evolving hydrological / hydraulic estimates* - The likelihood of a given magnitude flood event can vary significantly due to evolving hydrological / hydraulic estimates. For instance expected peak flows derived from flood frequency analysis can be altered by revisions made to the rating table or by extending the record length to include / exclude extreme events;

- *Climate Change* - Fundamental changes in the climate will alter the likelihood of flooding. This is discussed in Book 1, Chapter 5, Section 5 and Book 1, Chapter 6; and

- *Changes within the catchment and floodplain that alter flood flows and flowpaths*. This is discussed in Book 1, Chapter 5, Section 5.

This section discussed the first 3 dot points.

5.10.2. Changes to Consequence

Consequences of given magnitude flood events can change due to a wide range of variables including:

- Land-use change – change to a more vulnerable land use or to the degrees of exposure of development to flooding.

- Economic changes such as inflation.

- Changes to the community exposed to risk through long term or seasonal changes in the total population or its demographics. For example increases in population at holiday destinations and during festivals. A change in community demographics to include a higher proportion of people more vulnerable in emergency response can lead to increased consequences due to a flood.

- level of flood awareness / education in the community. The higher the level of community awareness of flooding the more the community will be to flood risk due to both their understanding of the need to and how to respond to a flood and the knowledge that they may need to take measures, such as having flood insurance to address some of their residual risk to flooding.

5.10.3. Changes to Risk Preference

Further, it is noted that, just as the components of risk (likelihood and consequence) may vary over time, so to an individual’s evaluation of the ultimate importance of that risk may alter. This may occur through:

- *Altered risk profiles* – Individuals tolerance for risk varies with their past and recent experience community attitudes to flood risk can vary significantly before and after a flood event; or

- *Risk discounting* – The value of a risk realised at a future time is typically considered of less significance than a risk realised at a current time. The rate at which this is applied may vary over time; typically the discount rate used reflects the economic discount rate in financial systems.

5.10.4. Literature

There is a range of literature that discusses how changes over time non-stationarity can be applied in risk assessments. Much of the work to date has occurred in the academic space (such as those of (Rootzen and Katz, 2013; Åström et al., 2013; Salas and Obeysekera, 2013)). This work indicates that there is potential for non-stationary models to be incorporated into design considerations and that the scale of catchment change may be of sufficient magnitude in some catchments to warrant consideration in design criteria. However, the costs of developing such models and assessments is likely to be prohibitive and unnecessary for the majority of flood- affected infrastructure, and that utilisation of traditional static risk profiles remains the more appropriate form of assessment.

For example, a method for incorporating design flood standards and design life into risk assessments is presented in (Rootzen and Katz, 2013). The paper proposes two methods to quantify risk for engineering design in a changing climate:

- The Design Life Level aims to achieve a desired probability of exceedance (or risk of failure) during the Design Service Life. This method is a SLEP approach (Book 1, Chapter 5, Section 4); or
- The Minimax Design Life Level is closely related, and complementary, but instead focuses on the maximal yearly probability of exceedance during the Design Service Life. This method is an AEP based approach.

The Design Life Level uses a Generalised Extreme Value (GEV) cumulative distribution function (cdf) to present the extremes in year *t*, and with increasing location and scale parameters (the shape parameter is constant) related to *t*, the probability changes. The example likens the increase in location parameter to a possible increase in water level, and scale parameter to an increase in climate variability. Another parameter is also introduced, the Expected Waiting Time (EWT) - the amount of time until a particular level *u* is exceeded.

Under this approach, if what is considered an acceptable level of risk is constant, it may be desirable to design mitigation measures (e.g. Design Flood Standards) such that the likelihood of a given consequence is constant in time. Figure 1.5.18 shows that if risk is increasing through time, then to keep the standard of risk protection constant, it would be necessary to continuously raise a defense. Clearly for many projects it is not possible to continually increase the capacity of flood protection measures, therefore if the mitigation measure is of fixed capacity the standard of risk protection varies with time (Figure 1.5.18).

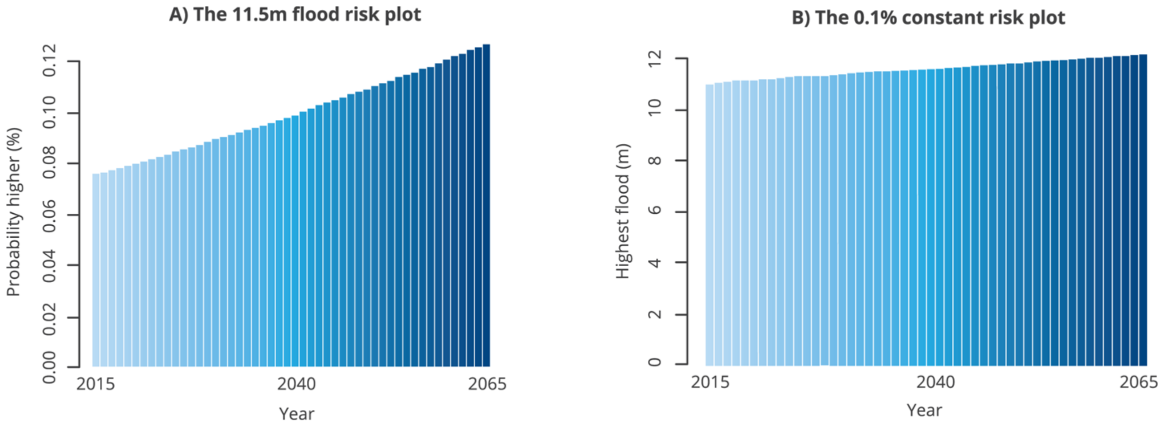

Figure 1.5.18. Flood Risk Plot Versus Constant Risk Plot (derived from Rootzen et al 2012)

Similarly, Salas and Obeysekera (2013) present a framework for addressing non-stationarity in risk assessment. The non-stationarity is considered in terms of increasing frequency of events, decreasing events and random shifting events, with standard return period and risk parameters. In the case of increasing extreme events, the exceedance probability of floods affecting structures also varies through time ie. $p_1, p_2, p_3, \ldots, p_t$. The sequence of p will also be increasing (Figure 1.5.19):

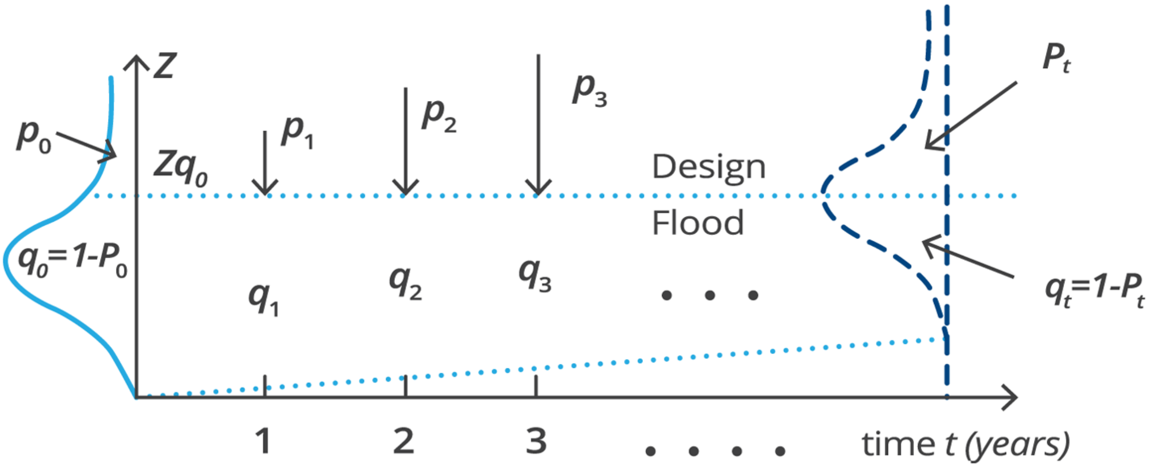

Figure 1.5.19. Schematic of a Design Flood with Exceeding (P_t) and Non-Exceeding ($q_t = 1-P_t$) Probabilities Varying with Time (Salas & Obeysekera, 2014)

This means that if the probability of the first flood exceeding the Design Flood Standard at time $x = 1$ is p_1, then the probability at time $x = 2$ is $(1 - p_1)p$. In general, the probability that the first flood exceeding the Design Flood Standard will occur at time x is given by:

$$f(x) = P(X = x) = (1 - p_1)(1 - p_2)(1 - p_3)\ldots(1 - p_{1-x})px \tag{1.5.1}$$

This geometric distribution is developed further for application in a non-stationary framework to allow the waiting time for the first exceedance of the Design Flood Standard to be calculated.

However, given the complexities of non-stationarity, the number of practical studies incorporating non-stationarity within flooding infrastructure is relatively low (e.g. Vogel et al. (2011), Condon et al. (2014), Ng and Vogel (2010) and Woodward et al. (2011)). Furthermore, there is limited application of these techniques in policy framework documents. In contrast, the majority of countries currently adopt coarse climate change adjustment factors to account for non-stationarity. Approaches within Australia are discussed in Book 1, Chapter 6[2].

However, there is broad guidance, such as AEMI (2013) that highlights the importance of considering how the floodplain and catchment will change overtime by encouraging both the understanding of cumulative impacts of new development and also considering the influence of a changing climate. These are generally undertaken separately to identify the sensitivity of changes due to these different changing factors. It is rare that all non-stationarity factors are considered together.

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[2] This section was written before the latest climate change guidance in Book 1, Chapter 6 (2024). A minor change to the text has been made to reflect the change in guidance.

5.10.5. Non-Stationary Risk Assessment

Non-stationarity is typically included in community risk based assessments (Book 1, Chapter 5, Section 5) by considering catchment and floodplain changes and climate change in understanding and managing flood risk to a community. However, for other infrastructure project, such as those identified inBook 1, Chapter 5, Section 6 to Book 1, Chapter 5, Section 8, non-stationary factors may need to be considered for the assessment.

5.10.5.1. Is a Non-Stationary Risk Assessment Required

In general, uncertainty in risk likelihood and consequence increases with a project's Effective Service Life. Some discussion on estimating effective service life are provided in Book 1, Chapter 5, Section 9.

Once the effective service life has been determined an assessment of the potentially likelihood of changes to risk (likelihood or consequence factors) should be undertaken. A discussion on climate change, and whether this is important for consideration, is provided in Book 1, Chapter 6.

Where a reasonable risk of change in other sources of non-stationarity is identified, a non-stationary risk assessment may be a preferred risk assessment approach. While this can be difficult to evaluate the following broad guidance is provided: in general, for medium to long term infrastructure (ie. with effective service life of greater than 5 years), it is suggested that:

- If the effective service life is less than 20 years a stationary risk assessment should be undertaken;
- If the effective service life is greater than 20 years but less than 50 years it is recommended that a non-stationary risk assessment be considered, except in areas in which the likelihood of change in local and regional land uses is minimal; and
- If the effective service life is greater than 50 years then it is recommended that a non-stationary risk assessment be undertaken.

The above is a general guidance, and does not take into account project specific issues. For both short-term and long-term infrastructure it is recommended that an initial review be undertaken that evaluates whether or not changes in likelihood and/or consequence (as listed above) are likely to occur over the Effective Service Life of the project and considering whether such changes would impair the project's ability to perform its intended function.

5.10.5.2. Non-Stationary Risk Assessment

Where non-stationary risk assessment is being considered, a process similar to non-stationary risk assessment can be undertaken. However, the non-stationary nature of the risks present will influence the design horizon over which the assessment is undertaken.

Rather than adopt the more complex models identified in Book 1, Chapter 5, Section 5, it is recommended to adopt a simple “time slice” approach. Primarily there are three approaches able to be adopted:

- **Undertake risk assessment at the point in time of highest overall risk (T(max))** : Typically, this may be at the end of the project's ESL. By applying the risk assessment at T(max), and determining appropriate design criteria for this point, the proponent will effectively design its infrastructure to be acceptable at all points of its ESL. This is considered to be the most conservative approach and will lead to relative over-engineering of infrastructure at some points of its life, particularly early in its life.

- **Undertake risk assessment based on the existing environment (T(0))** : This approach accepts that non-stationary components have impacts on flood behaviour, risks will rise. This approach assumes that this growth in risk will be acceptable and therefore it will lead to under-engineering relative to current minimum design requirements as risks rise. This is considered the least conservative approach and the most likely to result in higher long term risks.

- **Undertake risk assessment based on the existing environment (T(0)a) and commit to managing residual risk as it arises** : This approach will require periodic reassessment of risks associated with the project at agreed points in time. This approach may lead to under-engineering towards the end of the re-evaluation period and is considered the second least conservative approach.

- **Undertake risk assessment at a representative point in the projects ESL (T(x))** and commit to managing the residual risk: This approach will likely lead to over-engineering in the initial (pre – T(x)) period, after which it will require periodic reassessment of risks associated with the project at agreed points in time.

Each of these four options revolve around the choice between conservatively over-engineering to ensure risk levels are satisfied, against programs of continuous upgrades in which changes in risk may be responded to through adaptation in design.

In general the T(max) approach may be identified as the preferred approach where:

- The magnitude of change in risk is well known and likely to be small;
- A project's effective service life is certain;
- The costs of over-engineering are low; or
- The potential for retro-fitting / incorporating adaptability is low.

In contrast, The T(0)a and T(x) approaches are more likely to be favourable where:

- The potential change is risk is high or uncertain;
- The projects effective service life is uncertain;
- The costs of over-engineering are high; or
- The potential for incorporating adaptability is high.

There may be thresholds or tipping points at which the frequency of flooding or the consequences (e.g. loss of life, damage to residential property) of that flooding or the associated risks are considered unacceptable to the community. If these can be identified they can provide a basis for considering the limit of tolerability (LoT). With knowledge of the anticipated rate of change in the likelihood or consequence of flood events over time, it may be possible to approximate the time at which the LoT will be exceeded for any one consequence. Based upon current understanding of any such limits, beyond this point, flooding in association with a given project may be considered generate unacceptable risks.

This concept is basically a trigger based concept. For example, residential properties may be designed to a 1% AEP level, which is acceptable to the local authority. However, they are willing to tolerate a 2% AEP level if unavoidable. Currently, a residential development is built to a 1% AEP level. However, due to changes in the catchment (increase in impervious areas in the catchment) and climate change, this is expected to reduce to a 2% AEP level after 30 years. This represents a trigger point at which time a mitigation measure may need to be implemented.

Such points may be utilised as the minimum points at which risks, and the appetite for risk, are reassessed (T(0)a). Where current planning allows for adaptation, these can be considered the protected timeframe where this adaptation may be necessary based upon current knowledge and projections (T(x) Figure 1.5.20).

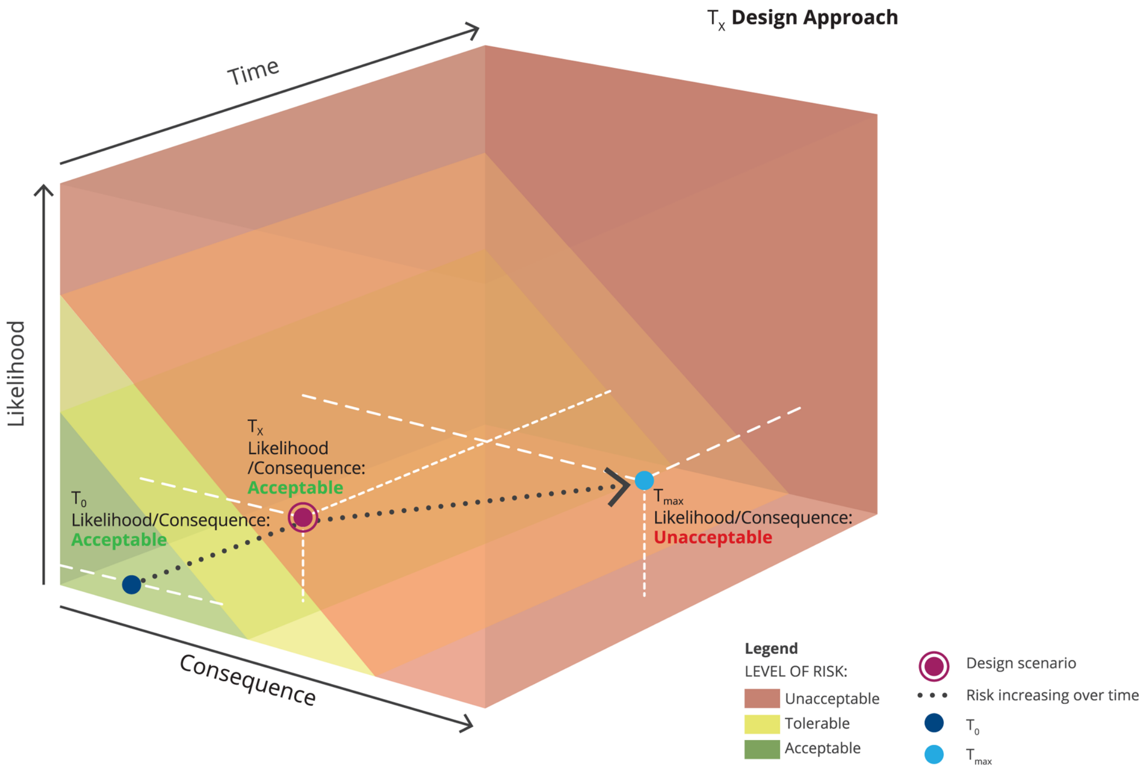

Figure 1.5.20. Change in Realised Risk Through Adopting a T(x) Design Approach.

From a practical perspective, consideration of the potential need for and likely methods for mitigating future growth in risk as part of the original decision can enable this work to be incorporated into upfront decisions (DECC, 2007). For example, land can be set aside or easements established to enable construction and maintenance of future mitigation measures. If this does not occur the mitigation measure may not be able to be implemented when required. Consideration of the costs of future mitigation in current decisions may in some cases influence the original decision on protection levels.

It is also noted that any option based around the future upgrade of infrastructure poses potential legal and commercial risks to both proponents and approval authorities. Given the extent of timeframe over which the infrastructure may be in place, the responsibility (and cost) of re-evaluation and upgrade in the future may change between individuals and there is the potential that the decision to upgrade at that time is not viable. In such circumstances the project may be decommissioned (these costs should be considered in any supporting economic analysis).

5.10.6. Economic Assessment

For non-stationary risk analysis, design options may be assessed through standard CBA evaluation of options. However, it is recommended that the changes over time be incorporated into the analysis. For example, the reduction in protection provided by a levee protecting a coastal town as flood levels change due to the increasing influence of coastal flooding as sea level rises due to climate change.

A simple approach for incorporating the changes over time is to take two or more time slices. For example, the flood inundation damages are calculated in year 0 and at the end of the Effective Service Life. Then the damages are assumed to change linearly between these two points. If the change is expected to occur differently, the more time slices may be required.

Adopting the methodology in Book 1, Chapter 5, Section 5, the key change is that the Annual Average Damage will progressively change over the Effective Service Life of the project. This can then be included into the economic assessment as described in Book 1, Chapter 5, Section 5.

There are several key considerations in undertaking economic analysis in non-stationary conditions:

Analysis Period

The inclusion of non-stationarity results in benefits and costs that vary through time. The important implication of this is that an economic outcome can be dependent on when the economic analysis period commences. For example, if we pay to construct a levee now to protect against climate change, then the cost is incurred in the present, but no real benefit may be realised for some time, for example twenty years. When the time value of money is considered in this scenario, it may be worth not investing in the levee until twenty years have passed.

This introduces a complication when comparing a number of alternative projects. Traditionally, you would be able to prioritise economically between projects based upon the larger BCR. However, the impact of non-stationarity introduces the dimension of time to the analysis. In other words, a project may not be viable now but may become viable in 10 years time. This type of assessment was applied in Thomson et al. (2011) and Thomson et al. (2012) for studies in the Solomon Islands.

An economic analysis under non-stationary conditions should be expanded to incorporate variable option implementation timing (ie. run CBA scenarios in which the project is developed in different phases over time). A CBA analysis could assess a range of scenarios (including staged scenarios) that capture this changing nature of costs and benefits over time.

Discount Rate

A challenge of non-stationary factors like climate change is that impacts which are experienced further into the future are diluted by standard discount rates. There is significant research that has been undertaken on appropriate discount rates for very long time periods. This is based on the argument that intergenerational equity should be considered, and that future generations should not be unfairly weighted compared with existing generations (Stern, 2006). This becomes particularly important for projects which are expected to have a relatively long effective service life, and therefore the benefits will span across multiple generations. Some recent studies, such as the Stern Review (Stern, 2006) have adopted very low discount rates (in the case of the Stern Review, 1.4%).

Some economists argue for zero discount rates when applied to environmental impacts. Quiggin (1993) goes further and suggests that the use of zero discount rates is in agreement with sustainability, where

“The interests of future generations should be given equal weight with our own in making decisions affecting the long term future”

Farber and Bradley (1996) suggest

“those changes that would enhance or degrade the human life support capacity of the ecosystem…. would not be discounted at all”

Philbert (2003) reviewed a number of approaches, and discussed that the discount rate may be derived not from the consumer perspective, but on a more general society perspective, based on “interpersonal comparisons”. There are inherent difficulties with this analysis. Philbert (2003) argues that the current generation will incur costs for the benefit of future generations, but there will reach a point at which perceived gain for the next generation is not seen as worth the cost for the present generation. Therefore, a zero discount rate should not apply, as it would imply “very high investment by the present generation”. Philbert (2003) suggests a discount rate that decreases over time, approaching the “lowest reasonably foreseeable rate” of economic growth. Philbert (2003) also suggests potentially increasing the value of environmental assets, as these are progressively consumed moving into the future.

Most of the discussion in relation to varying of discount rates focuses in on climate change and environmental policies. These policies, such as emission trading schemes, can result in costs now, in order to off-set potential significant costs in the future and impacts that may not be possible to be rectified by future generations.

The challenge with varying the discount rate is that it results in difficulties in comparing across projects. For example, if one project adopts a discount rate of 7% and another a discount rate of 4%, then it is difficult to directly compare the BCR results of such studies without thoroughly understanding the underlying assumptions.

For the purposes of the majority of water related infrastructure, and to ensure consistency across projects, it is recommended to adopt typical discount rates. Treasury guidance may recommend discount rates to provide consistency across competing projects. However, the above should be kept in mind for policies and planning that is targeting impacts well into the future.

Alternative Economic Models

Alternatively, a more robust economic analysis approach would be the use of Real Options Analysis (ROA). ROA is a recognised approach to address the uncertainties of future conditions in flood risk management by accounting for flexibility in investment decision (World Bank, 2010; Short et al., 2012; Park et al., 2014; HM Treasury and DEFRA, 2009).

The standard CBA approach is a relatively coarse mechanism in which costs and benefits assessed are considered as a whole and do not allow for discernment of the manner in which they accrue (e.g. changes in the rate at which benefits are received may not justify development of all project components as part of initial project construction). Neither does the analysis recognise that estimates of cost, benefit and risk into the future are inherently uncertain. As such, deferring decisions on infrastructure investment until a later date when more information is available may be the preferred approach. ROA allows the value of deferring investment decisions to be assessed.

In ROA, “options” represent predefined choices over a project’s Effective Service Life that strategically or operationally affects the course of the project. For example, a project may be to build a levee. If we build the levee in such a way that it is possible for it to be upgraded at a later date, a real option may be to increase levee height by 0.5m. The analysis defines decision points at which these choices are made (e.g. T(x)). The decision points can be points may be fixed in time or variable and triggered by internal or external events (e.g. occurrence of a 1% AEP event). Based on the Black-Scholes model utilised in financial options analysis, ROA utilises estimates of volatility (ie. the likelihood of a particular flood event or level of damage occurring in one year) to evaluate expected values/damages that are likely to be incurred over the Effective Service Life. The establishment of appropriate volatility measures is critical to ROA, and not all systems will have readily discernible volatilities.

For example, a flood levee may be required and it is known that currently it needs to be built to a 20% AEP in order to maintain an acceptable level of risk. However, it is also forecast that due to climate change, over 50 years, the magnitude of the 20% AEP event will be equivalent to the magnitude of the current 10% AEP event and that levee would need to be increased by one metre in height to provide the same level of risk. Assume, also that the volatility is such that there was 50% chance that the cost of flooding would increase by 5% per year and a 50% chance that the cost of flooding would increase by 1% per year. Utilising a numerical method for the pricing of options (e.g. the Binomial Method, Black-Scholes Model), and based on this volatility year on year, it would be possible to estimate the value of implementing an option in a given year (ie. the value of waiting to make a decision on investing until more information is available). For example, if it turns out that by year 10 that there have been 10 consecutive 5% increases, then the benefits of increasing the height of the levee at that point will be significantly greater than if there had been 10 consecutive 1% increases per year.

Other common decision-under-uncertainty making tools which may be utilised include Laplace’s Principle of Insufficient Reason or Walds Maximin Model.

5.11. Further Reading

SCARM (2000) Floodplain Management in Australia: Best Practice Principles and Guidelines. Agriculture and Resource Management Council of Australia and New Zealand, Standing Committee on Agriculture and Resource Management (SCARM). Report No 73. CSIRO Publishing, 2000.

Shand, T. D., Cox, R. J., Blacka, M. J. and Smith, G. P. (2011). Australian Rainfall and Runoff Revision Project 10: Appropriate Safety Criteria for Vehicles - Literature Review. Australian Rainfall and Runoff Revision Project 10. Stage 2 Report. Prepared by the Water Research Laboratory. P10/S2/020. February 2011.

Opper S, Emergency Management Planning for the Hawkesbury Nepean Valley, 40th Floodplain Management Authorities Conference, Parramatta, 9th – 12th May 2000.

NSW Government (2005). Floodplain Development Manual. Department Of Infrastructure Planning and Natural Resources. DIPNR 05_020.

NFRAG (2008) Flood Risk Management in Australia. The Australian Journal of Emergency Management. Vol 23, No. 4, November 2008.

McLuckie, D., Babister M., (2015). Improving national best practice in flood risk management, Floodplain Management Association National Conference, Brisbane, May 2015.

McLuckie, D., Babister M., Smith G., Thomson R., (2014). Updating National best practice guidance in flood risk management, Floodplain Management Association National Conference, Deniliquin, May 2014.

McLuckie, D., (2013). A guide to best practice in flood risk management in Australia, Floodplain Management Association National Conference, Tweed Heads, May 2013.

McLuckie, D., (2012). Best Practice in Flood Risk Management in Australia. Presentation to Engineers Australia Queensland Water Panel, Brisbane, May 2012.

COST 2013 - A review of applied methods in Europe for flood-frequency analysis in a changing environment: WG4 – Flood Frequency estimation methods and environmental change.

Babister, M., Retallick, M., 2013. Benchmarking Best Practice in Floodplain Management, Floodplain Management Association National Conference, Tweed Heads, May 2013

Babister, M., McLuckie, D., Retallick, M., Testoni, I. (2014). Comparing Modelling Approaches to End User needs, Floodplain Management Association Conference, Deniliquin, May 2014

5.12. Examples

5.12.1. Calculation of Average Annual Damages for a Community

$$\mathrm{AAD} = \left[\text{Sum from 1 to n of, } \frac{d_1 + d_2}{2}(p_2 - p_1) + \frac{d_2 + d_3}{2}(p_3 - p_2) + \ldots, \frac{d_{n-1} + d_n}{2}(p_n - p_{n-1})\right]$$

Where:

AAD = Annual Average Damages in $

d = damage in $

p = probability

points 1 to n are the different ordinates on the damage curve

Example:

Determine the damage under the curve for Figure 1.5.3. The table below provides the points on the curve.

AEP	Flood Damage for Event ($)	n
0.001%	$28,000,000	1
0.2%	$22,000,000	2
0.5%	$20,000,000	3
1.0%	$17,000,000	4

2.0%	$9,000,000	5
5.0%	$3,000,000	6
10%	$1,000,000	7
20%	$0	8

$$\mathrm{AAD} =$$

$$\left[\begin{array}{l} \left(\frac{28,000,000 + 22,000,000}{2} x(0.002 - 0.0001)\right) + \left(\frac{22,000,000 + 20,000,000}{2} x(0.005 - 0.002)\right) \\ + \left(\frac{20,000,000 + 17,000,000}{2} x(0.01 - 0.005)\right) + \left(\frac{17,000,000 + 9,000,000}{2} x(0.02 - 0.01)\right) \\ + \left(\frac{9,000,000 + 3,000,000}{2} x(0.05 - 0.02)\right) + \left(\frac{3,000,000 + 1,000,000}{2} x(0.1 - 0.05)\right) \\ + \left(\frac{1,000,000 + 0}{2} x(0.2 - 0.1)\right) \end{array} \right]$$

$$\mathrm{AAD} = [49,750 + 63,000 + 92,500 + 130,000 + 180,000 + 100,000 + 50,000]$$

$$\mathrm{AAD} = \$665,250$$

When it comes to examining treatment options it can be important to understand which portion of the curve is contributing significantly to damage and therefore a table such as follows can be useful. In this case events up to a 1% AEP event contribute $460,000 out of the $665,250 toward Annual Average Damages.

AEP n	AEP n-1	Flood Damage n ($)	Flood Damage n-1 ($)	Contribution to AAD ($)
0.001%	0.2%	$28,000,000	$22,000,000	$49,750
0.2%	0.5%	$22,000,000	$20,000,000	$63,000
0.5%	1.0%	$20,000,000	$17,000,000	$92,500
1.0%	2.0%	$17,000,000	$9,000,000	$130,000
2.0%	5.0%	$9,000,000	$3,000,000	$180,000
5.0%	10%	$3,000,000	$1,000,000	$100,000

10%	20%	$1,000,000	$0	$50,000
Total ($)	n/a	n/a	n/a	$665,250

5.12.2. Calculating Average Annual Benefits of a Treatment Measure

$\mathrm{AAB} = \mathrm{AAD}_{case0} - AAD_{case1}$

Where:

AAB = annual average benefits in $

AAD = annual average damages in $ - calculations see Book 1, Chapter 5, Section 12

Case 0 is the current situation or base case

Case 1 is the case with treatment in place

Example:

Determine the Average Annual Benefits

Step 1

Determine Annual Average Damages for the base case – undertaken in Book 1, Chapter 5, Section 12

Step 2

Determine Annual Average Damages for the treated case. See table below.

AEP n	AEP n-1	Flood Damage n ($)	Flood Damage n-1 ($)	Contribution to AAD ($)
0.001%	0.2%	$28,000,000	$22,000,000	$49,750
0.2%	0.5%	$22,000,000	$15,000,000	$55,500
0.5%	1.0%	$15,000,000	$2,000,000	$42,500
1.0%	2.0%	$2,000,000	$750,000	$13,750
2.0%	5.0%	$750,000	$500,000	$18,750
5.0%	10%	$500,000	$200,000	$17,500
10%	20%	$200,000	$0	$10,000
Total ($)	n/a	n/a	n/a	$207,750

Step 3

Determine Annual Average Damages for the base case – undertaken in Book 1, Chapter 5, Section 12

Step 4

Determine Annual Average Damages for the treated case. See table below.

AEP n	AEP n-1	Base Case Contribution to AAD From Book	Treated Case Contribution to AAD ($)	Contribution to AAB ($)

		1, Chapter 5, Section 12		
0.001%	0.2%	$49,750	$49,750	$0
0.2%	0.5%	$63,000	$55,500	$7,500
0.5%	1.0%	$92,500	$42,500	$50,000
1.0%	2.0%	$130,000	$13,750	$116,250
2.0%	5.0%	$180,000	$18,750	$161,250
5.0%	10%	$100,000	$17,500	$82,500
10%	20%	$50,000	$10,000	$40,000
Total ($)	n/a	$665,250	$207,750	$457,500

5.12.3. Calculating Net Present Value of Benefits

$$\mathrm{NPV} = \left[\text{Sum 1 to } n-1 \text{ of, } \frac{\mathrm{AAB}}{(1+\mathrm{dr})^{1}} + \frac{\mathrm{AAB}}{(1+\mathrm{dr})^{2}} + \ldots, \frac{\mathrm{AAB}}{(1+\mathrm{dr})^{(n-1)}}\right]$$

Where:

AAB = Annual Average Benefits in $ - calculation see Book 1, Chapter 5, Section 12

dr = discount rate

n= design life in years. Assumes no benefits during construction.

Note:

A range of discount rates may be used to give a range of NPVs which can in turn be used to determine a range of Benefit Cost Ratios (see Book 1, Chapter 5, Section 12) to test how financial benefits may vary with different financial situations.

Example:

Calculating Net Present Value of benefits

Step 1

Determine the Average Annual Benefits – undertaken in Book 1, Chapter 5, Section 12

Step 2

Assess Net Present Value of benefits. See table below.

$\mathrm{NPV}_{\mathrm{Benefits}} = \$6,099,257$ for a discount rate (dr) of 7%. This could vary from $4,473,916 for a dr of 10% to $9,055,194 for a dr of 4%.

Year N	Benefit in Future Year AAB ($)	Benefit in future year in current year for dr_1 = 4% ($)	Benefit in future year in current year for dr_2 = 7% ($)	Benefit in future year in current year for dr_3 = 10% ($)
0	0	0	0	0
1	457,500	439,904	427,570	415,909
2	457,500	422,984	399,598	378,099
3	457,500	406,716	373,456	343,727

4	457,500	391,073	349,025	312,479
5	457,500	376,032	326,191	284,072
6	457,500	361,569	304,852	258,247
7	457,500	347,662	284,908	234,770
8	457,500	334,291	266,269	213,427
9	457,500	321,433	248,850	194,025
10	457,500	309,071	232,570	176,386
11	457,500	297,183	217,355	160,351
12	457,500	285,753	203,135	145,774
13	457,500	274,763	189,846	132,521
14	457,500	264,195	177,426	120,474
15	457,500	254,034	165,819	109,522
16	457,500	244,263	154,971	99,565
17	457,500	234,868	144,833	90,514
18	457,500	225,835	135,358	82,285
19	457,500	217,149	126,503	74,805
20	457,500	208,797	118,227	68,004
21	457,500	200,766	110,492	61,822
22	457,500	193,045	103,264	56,202
23	457,500	185,620	96,508	51,093
24	457,500	178,481	90,195	46,448
25	457,500	171,616	84,294	42,225
26	457,500	165,015	78,779	38,387
27	457,500	158,669	73,626	34,897
28	457,500	152,566	68,809	31,725
29	457,500	146,698	64,307	28,841
30	457,500	141,056	60,100	26,219
31	457,500	135,631	56,169	23,835
32	457,500	130,414	52,494	21,668
33	457,500	125,398	49,060	19,698
34	457,500	120,575	45,850	17,908
35	457,500	115,938	42,851	16,280
36	457,500	111,478	40,047	14,800
37	457,500	107,191	37,428	13,454
38	457,500	103,068	34,979	12,231
39	457,500	99,104	32,691	11,119
40	457,500	95,292	30,552	10,108

Total ($)	$9,055,194	$6,099,257	$4,473,916

5.12.4. Calculating Net Present Value (NPV) of Lifecycle Costs

$$\mathrm{NPV} = \mathrm{Capital\ Cost} + \left[\mathrm{Sum\ 1\ to\ } n - 1 \mathrm{\ of,\ } \frac{\mathrm{AMC}}{(1+\mathrm{dr})^{1}} + \frac{\mathrm{AMC}}{(1+\mathrm{dr})^{2}} + \ldots, \frac{\mathrm{AMC}}{(1+\mathrm{dr})^{(n-1)}}\right]$$

Where:

Capital cost is all relevant upfront costs.

AMC = Annual operation and Maintenance Costs

dr = discount rate

n= design life in years. Assumes no benefits during construction.

Note:

A range of discount rates may be used to give a range of NPVs and in turn a range of Benefit Cost Ratios (see Book 1, Chapter 5, Section 12) to test how financial benefits may vary with changing financial situation.

Example:

Calculating Net Present Value of lifecycle costs

Step 1

Determine capital costs and Annual operation and Maintenance Costs

Step 2

Calculate Net Present Value of lifecycle costs. See table below.

Example:

Capital cost is $4,000,000 and Annual operation and Maintenance Costs is $100,000.

$\mathrm{NPV}_{\mathrm{costs}} = \$5,333,171$ for a discount rate (dr) of 7%. This could vary from $4,977,105 for a dr of 10% to $5,979,277 for a dr of 4%.

Year N	Cost in Future Year AAB ($)	Cost in future year in current year for dr_1 = 4% ($)	Cost in future year in current year for dr_2 = 7% ($)	Cost in future year in current year for dr_3 = 10% ($)
0	4,000,000	4,000,000	4,000,000	4,000,000
1	100,000	96,154	93,458	90,909
2	100,000	92,456	87,344	82,645
3	100,000	88,900	81,630	75,131
4	100,000	85,480	76,290	68,301
5	100,000	82,193	71,299	62,092
6	100,000	79,031	66,634	56,447
7	100,000	75,992	62,275	51,316
8	100,000	73,069	58,201	46,651

9	100,000	70,259	54,393	42,410
10	100,000	67,556	50,835	38,554
11	100,000	64,958	47,509	35,049
12	100,000	62,460	44,401	31,863
13	100,000	60,057	41,496	28,966
14	100,000	57,748	38,782	26,333
15	100,000	55,526	36,245	23,939
16	100,000	53,391	33,873	21,763
17	100,000	51,337	31,657	19,784
18	100,000	49,363	29,586	17,986
19	100,000	47,464	27,651	16,351
20	100,000	45,639	25,842	14,864
21	100,000	43,883	24,151	13,513
22	100,000	42,196	22,571	12,285
23	100,000	40,573	21,095	11,168
24	100,000	39,012	19,715	10,153
25	100,000	37,512	18,425	9,230
26	100,000	36,069	17,220	8,391
27	100,000	34,682	16,093	7,628
28	100,000	33,348	15,040	6,934
29	100,000	32,065	14,056	6,304
30	100,000	30,832	13,137	5,731
31	100,000	29,646	12,277	5,210
32	100,000	28,506	11,474	4,736
33	100,000	27,409	10,723	4,306
34	100,000	26,355	10,022	3,914
35	100,000	25,342	9,366	3,558
36	100,000	24,367	8,754	3,235
37	100,000	23,430	8,181	2,941
38	100,000	22,529	7,646	2,673
39	100,000	21,662	7,146	2,430
40	100,000	20,829	6,678	2,209
Total ($)		$5,979,277	$5,333,171	$4,977,905

5.12.5. Calculating Benefit Cost Ratio (BCR)

$$\mathrm{BCR} = \frac{\mathrm{NPV}_{\mathrm{benefits}}}{\mathrm{NPV}_{\mathrm{costs}}}$$

Where:

$\text{BCR}{=}\text{Benefit Cost Ratio}$

$\text{NPV}_{\text{benefits}} = \text{Net Present Value of Benefits}$ - see Book 1, Chapter 5, Section 12

$\text{NPV}_{\text{costs}} = \text{Net Present Value of Costs}$ - see Book 1, Chapter 5, Section 12

Note:

A range of discount rates may be used to give a range of NPVs which can in turn be used to determine a range of Benefit Cost Ratios (see below) to test how financial benefits may vary with different financial situations.

Example:

Calculating BCR

Step 1

Calculate $\text{Net Present Value of Benefits} = \text{NPV}_{\text{benefits}}$

Step 2

Calculate $\text{Net Present Value of Costs} = \text{NPV}_{\text{costs}}$

Step 3

Calculate BCR. BCR = 1.14 for dr 7%, BCR = 1.51 for dr 4%, BCR = 0.9 for dr 10%.

Discount Rate dr (%)	NPV benefits ($)	NPV costs ($)	BCR
4	9,055,194	5,979,277	1.51
7	6,099,257	5,333,171	1.14
10	4,473,916	4,977,905	0.90

5.13. References

AEMI (Australian Emergency Management Institute) (2013), Australian Emergency Management Handbook 7: Managing the Floodplain Best Practice in Flood Risk Management in Australia AEMI, Canberra.

AEMI (Australian Emergency Management Institute) (2015), Australian Emergency Management Handbook 10: National Emergency Risk Assessment Guidelines AEMI, Canberra.

AEMI (Australian Emergency Management Institute) (2014a), Technical flood risk management guideline: Flood emergency response classification of the floodplain, AEMI, Canberra.

AEMI (Australian Emergency Management Institute) (2014b), Technical flood risk management guideline: Flood hazard, AEMI, Canberra.

AEMI (Australian Emergency Management Institute) (2014c), Guideline for using the national generic brief for flood investigations to develop project-specific specifications, AEMI, Canberra.

ANCOLD (Australian National Committee on Large Dams) (2003), Guidelines on Risk Assessment. Australian National Committee on Large Dams.

AUSTROADS (1994), Waterway Design: A Guide to the Hydraulic Design of Bridges, Culverts and Floodways, Ed: D. Flavell.

Condon, L.C., Gangopadhyay, S. and Pruitt, T. (2014), Climate change and non-stationary flood risk for the Upper Truckee River Basin. Hydrological Earth System Sciences Discussions, 11: 5077-5114.

DECC (NSW Department of Environment and Climate Change), (2007), Floodplain Risk Management Guideline, Residential Flood Damage, Sydney.

Farber, S. and Bradley, D. (1996), Ecological Economics. USDA Forest Service, available at: http://www.fs.fed.us.

Floodplain Regulations Committee (2010), A Guide for Higher Standard in Floodplain Management. Association of State Floodplain Managers.

HM Treasury and DEFRA (2009), Accounting for the effects of climate change: Supplementary Green Book Guidance.

ISO (International Standards Organisation). (2009a), Guide 73:2009 Risk Management Vocabulary, International Standards Organisation.

ISO (International Standards Organisation). (2009b), International Standard on Risk Management, ISO31000:2009, International Standards Organisation.

McLuckie, D., Toniato A., Askew E., Babister M. and Retallick M. (2016), Supporting Land Use Planning by providing improved information from the Floodplain Management Process, Floodplain Management Association Conference, Nowra, May 2016.

Ng, M. and Vogel, R.M. (2010), Multivariate non-stationary stochastic streamflow models for two urban watersheds. Proc., Environmental and Water Resources Institute World Congress, ASCE, Reston, VA, pp: 2550-2561.

Park, T., Kim, C. and Kim, H. (2014), Valuation of drainage infrastructure improvement under climate change using real options. Water Resource Management, 28: 445-457.

Philbert C. (2003), Discounting the Future. In: Internet Encyclopaedia of Ecological Economics, The International Society of Ecological Economics. Available at: http://www.ecologicaleconomics.org.

Quiggin J. (1993), Discounting and Sustainability. Review of Marketing and Agricultural Economics, 6(1), 161-64.

Rootzen, H. and Katz, R. (2013), Design Life Level: Quantifying risk in a changing climate. Water Resources Research, 49: 5964-5972.

Salas, J. and Obeysekera, J. (2013), Revisiting the concepts of return period and risk for nonstationary hydrologic extreme events. Journal of Hydologic Engineering, 19(3), 554-568.

Short, M., Peirson, W., Peters, G. and Cox, R. (2012), Managing adaptation of urban water systems in a changing climate. Water Resources Management, 26(7), 1953-1981

Stern, N. (2006), The Economics of Climate Change - The Stern Review, Cabinet Office - HM Treasury, Cambridge University Press. Available at: http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/sternreview_index.htm.

Thomson, R., Knee, P., Telford, T., Virivolomo, M. and Drynan, L. (2011), Climate Change Adaptation & Economics - A Case Study in the Solomon Islands, Coast and Ports Conference, Perth, Australia.

Thomson, R., Knee, P., Telford, T., Virivolomo, M. and Drynan, L. (2012), Incorporating Climate Change into Economic Analysis - A Case Study of Emergency Flood Repairs in the Solomon Islands, Practical Responses to Climate Change, Canberra, Australia.

Vogel, R.M., Yaindl, C. and Walter, M. (2011), Nonstationarity: Flood magnification and recurrence reduction factors in the United States, J. Am. Water Resour. Assoc., 47: 464-474.

Woodward, M., Gouldby, B., Kapelan, Z., Khu, S. and Townend, I. (2011), Incorporating real options into flood risk management decision making. 14th annual international real options conference.

World Bank (2010), Economics of adaptation to climate change: synthesis report. Washington D.C.

Åström, H., Friis Hansen, P., Garré, L. and Arnbjerg-Nielsen, K. (2013), An influence diagram for urban flood risk assessment through pluvial flood hazards under non-stationary conditions. NOVATECH.

Chapter 6. Climate Change Considerations

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6.1. Introduction

Key messages

Because our climate is changing, unadjusted historical observations are no longer a suitable basis for design flood estimation: they must be adjusted to reflect the impacts of rising global temperatures. This chapter provides guidance on how to do this. It is based on a systematic review and meta-analysis of recent peer-reviewed science.

There is unequivocal evidence that greenhouse gas emissions have caused global warming. The Intergovernmental Panel on Climate Change's sixth assessment report concluded that global surface temperatures have significantly increased above pre-industrial levels, with significant further warming expected (IPCC, 2023). This warming is causing an increase in many drivers of flood risk, including an intensification of extreme rainfall events and the elevation of average and extreme sea levels (IPCC, 2023).

Traditionally, design flood estimation has assumed that historical observations are representative of current and future conditions. This is no longer the case. Records on historical flooding or flood drivers (such as extreme rainfall or sea level) can no longer be assumed to provide a direct analogue of current or future flood risk. To account for significant observed and projected changes to the drivers of flooding, it is necessary to account for the non-stationarity of flooding in the assessment of current and future flood risks.

This chapter provides practitioners, designers, and decision makers with guidance on how to assess the impact of climate change on design flood characteristics. As with the rest of *Australian Rainfall and Runoff* (ARR) the content is advisory, so additional guidance or requirements may need to be sought from relevant government regulation in the jurisdiction of interest.

This chapter replaces the 2019 Climate Change Considerations chapter (Bates et al., 2019) in Book 1, Chapter 6 of ARR Version 4.1. This chapter provides guidance that reflects the contemporary science, is applicable across the range of design flood approaches, and facilitates consistent application of climate change in design flood estimation. This guidance is based on an extensive and rigorous systematic review and meta-analysis of over 300 distinct peer-reviewed scientific studies published largely from 2011 onwards. For further information on the scientific basis for this guidance, readers are referred to Wasko et al. (2024).

Key differences from the 2019 Climate Change Considerations chapter (Version 4.1) include:

- recognition that global temperatures have increased over the historical period used to derive design rainfall information
- a recommendation to adjust 2016 Intensity-Frequency-Duration (IFD) curves to present (i.e. current climate) conditions
- provision of information to support a range of approaches to decision-making
- provision of guidance across the range of Annual Exceedance Probability (AEP) considered in ARR up to and including the Probable Maximum Precipitation (PMP)
- provision of uncertainty estimates
- consideration of additional factors that influence design flood estimates; that is, changes in rainfall losses, temporal patterns, and sea level rise.

This chapter is structured as follows:

- Book 1, Chapter 6, Section 2 discusses the 2 primary types of uncertainty exacerbated by climate change that are relevant to flood design.
- Book 1, Chapter 6, Section 3 covers how climate change affects design flood estimation methods more broadly.
- Book 1, Chapter 6, Section 4 describes how to account for climate change in the key aspects of event-based design flood estimation, with the recommendations linked to the worked examples in Book 1, Chapter 6, Section 6.
- Book 1, Chapter 6, Section 5 recommends an approach for future updates to the climate change considerations chapter.
- Book 1, Chapter 6, Section 6 provides worked examples of the guidance presented in Book 1, Chapter 6, Section 4.

6.2. Decison Contexts for Flood Guidance

Key messages

Climate variability heavily influences the risks of flooding from one time period to the next (‘aleatory uncertainty’) and these risks will shift under climate change. There is considerable uncertainty associated with future global emissions and the physical effects of these emissions on flood drivers increases the uncertainty of design flood estimates (‘epistemic uncertainty’). A user needs to choose their approach to design flood estimation in the context of these two sources of uncertainty.

ARR provides guidance to support the estimation of design floods that inform either standards-based design criteria (such as designing to the 1% AEP standard) or risk-based approaches that seek to understand flood behaviour across a range of flood magnitudes up to and including the Probable Maximum Flood (PMF) (see Book 1, Chapter 5 for more detail). Guidance in ARR is largely focused on dealing with the inherent randomness of factors (the aleatory uncertainties) that influence the exceedance probability of a given event (Book 4, Chapter 3). In rainfall-based estimates this most often involves consideration of Intensity-Frequency-Duration (IFD) rainfall bursts (Book 2, Chapter 3), variability in rainfall temporal patterns (Book 2, Chapter 5), and the influence of antecedent and event losses

(Book 5, Chapter 3). In techniques based on the direct analysis of flood data (Book 3), the aleatory uncertainty of these factors is implicitly accounted for in the sampling variability represented in the available flood observations. Climate change is now impacting the frequency and behaviour of many of the factors that influence flood behaviour resulting in non-stationarity in design flood estimates, shifting estimates of the aleatory uncertainty (Figure 1.6.1).

While much of the emphasis of climate science is to understand the likely historical and future changes to key flood risk drivers, another important consequence of climate change is an increase in the epistemic uncertainty of design flood estimates (Figure 1.6.1). This additional uncertainty arises from limitations in data and knowledge, where in the context of climate change this includes the uncertainty associated with future global emissions and mitigation strategies, resultant uncertainty in future global and regional temperature changes, and uncertainties on the implication of changing temperatures and associated processes on flood risk drivers. Within risk-based decision-making frameworks (where risk is commonly defined as 'the effect of uncertainty on objectives', ISO 31000), considerations of the projected changes in flood risk drivers as well as the increasing level of uncertainty associated with those drivers are both relevant in assessment of overall risk.

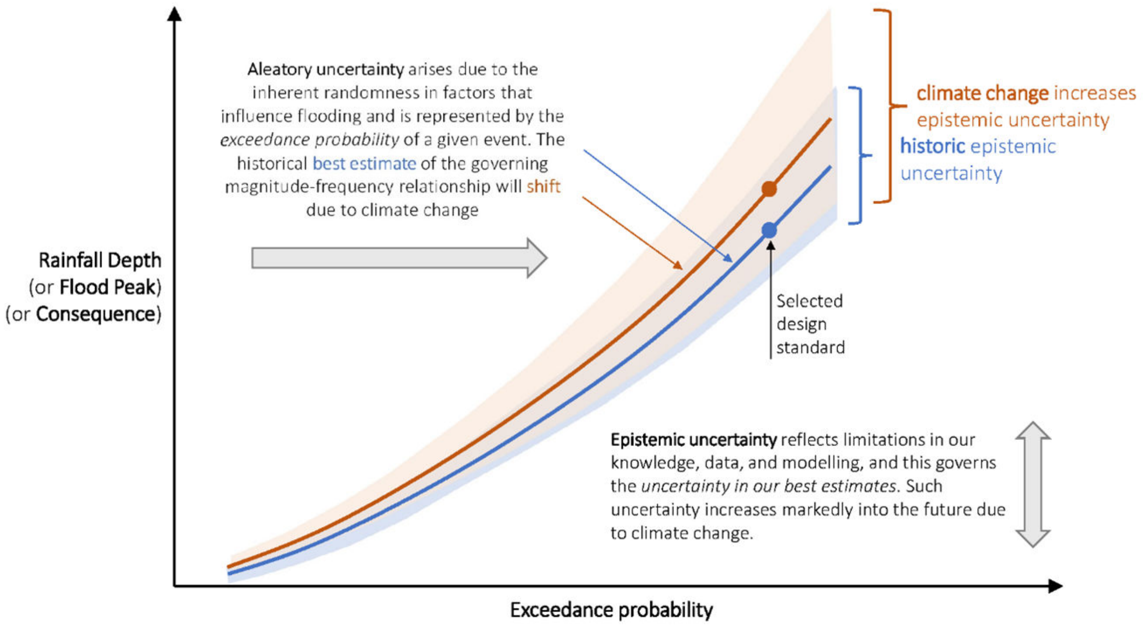

Figure 1.6.1. Climate Change is shifting our best estimate of the relationship between event magnitude and frequency and increasing the inherent uncertainty in such estimates

In addition to standards-based and risk-based decision-making approaches, there has recently been interest in decision-making frameworks that are less reliant on annualised probability-based estimates of flood magnitude. Examples include robust design approaches that can adapt to changes in design flood estimates over time (adaptive management), sensitivity and stress-testing approaches that explore the effect of alternative assumptions on decision-making ('bottom-up' and 'decision-scaling' approaches), and 'storyline' methods that often draw on historical flood events, but which are modified to account for potential impacts of climate change.

This chapter provides guidance for future changes to design floods recognising the requirements of current design procedures (and the need to capture the shifts in the magnitude-frequency relationships relevant to both standards-based and risk-based decision-making approaches), while also providing information to assist in estimating the uncertainty associated with those best estimates. This allows for consistency in the guidance here and the above decision-making frameworks. For example, a standards-based approach may adopt the median values presented in Book 1, Chapter 6, Section 4 and incorporate the uncertainty in a Monte Carlo framework. A bottom-up approach may use the uncertainty as a guide for sensitivity testing to develop system response surfaces for the hazard of interest. A risk-based approach may consider the probabilities and consequences of flooding across a range of exceedance probabilities, accounting for both aleatory and epistemic uncertainties.

The reader is referred to Book 1, Chapter 5 for further information on risk-based decision making, with Book 1, Chapter 5, Section 10 detailing a possible process of undertaking a non-stationary risk assessment. Further information on approaches for representing epistemic uncertainty as part of the design flood estimation process are presented in Book 7, Chapter 9, with the different approaches to address aleatory uncertainty described in Book 1, Chapter 3.

6.3. Selection of a Design Flood Estimation Method Under Climate Change

Key messages

There are two broad classes of design flood estimation methods: direct flood-based procedures and rainfall-based procedures. Rainfall-based procedures can be further divided into continuous and event-based approaches. The impacts of climate change are most readily incorporated into event-based methods, and hence this guidance focusses on generic advice that is relevant to these methods. Direct flood-based procedures (e.g. flood frequency) and continuous simulation approaches remain important tools for the assessment of flood risk, though there is no clear consensus on how such methods should be adjusted to account for climate change.

Although frequency analysis will continue to be used for design flood estimation and the calibration of models to historic data, climate change influences a range of flood drivers which impact on flood magnitude in a highly non-linear fashion. It is thus difficult to directly adjust flood information without reference to the causal processes by which climate change influences flood magnitude (Wasko et al., 2024). This means that extrapolating historical trends into the future or scaling historical flood magnitudes by a fixed amount may not adequately capture how changes in the causal drivers propagate through a catchment to influence changes in flood behaviour. Accordingly, it is recommended that any adjustment of historical flood frequency estimates to account for climate change be undertaken in a manner that it is consistent with the impact of changes in the flood drivers (e.g. extreme rainfall, antecedent conditions, sea level, etc) as described in this chapter.

In contrast to flood-based procedures, rainfall-based procedures provide a mechanism to relate information on climate projections to design flood estimates using either event-based or continuous simulation approaches. For continuous simulation to be suitable for flood estimation under a non-stationary climate, the timeseries need to reflect the complexities of future changes that are relevant to the design flood estimation problem. As highlighted in Wasko et al. (2024), extreme rainfall is likely to change at a different rate to annual average rainfall. Similarly short-duration extremes (sub-daily rainfall) and longer-duration extremes (multi-day accumulations) are likely to be experiencing differing rates of change in both frequency and intensity, leading to complex changes in the temporal patterns of rainfall. There may also be changes to the seasonality of heavy rainfall events, and to the sequencing of wet and dry periods.

Although continuous simulation approaches can be adapted to use climate-adjusted input timeseries (rainfall and potential evapotranspiration), further research is required to develop robust and practical methods to generate these climate-adjusted inputs into continuous simulation models, and applications will generally require the development of individualised solutions. As a pragmatic minimum, it is recommended that extreme rainfalls in the timeseries used for continuous simulation be scaled to reflect the recommendations for incorporating climate change into Intensity-Frequency-Duration curves (Book 1, Chapter 6, Section 4), with the remaining rainfalls adjusted to reflect projections of the mean seasonal or annual rainfall for the location of interest. Suitable account will also need to be given to adjusting evaporative demand inputs.

Due to the above considerations, and because event-based procedures are commonly applied in design flood estimation, event-based procedures are recommended as the primary class of procedures for incorporating climate change into design flood estimates. In the context of climate change assessments, the advantages of this class of procedures are the ability to clearly map climate projections (including those related to extreme rainfall and/or sea levels) to the inputs of event-based rainfall-runoff and hydraulic models, together with their general applicability across both gauged and ungauged catchments and for a wide range of annual exceedance probabilities from the 1 exceedance per year (EY) event through to the Probable Maximum Precipitation (PMP) (Figure 1.3.2 of Book 1, Chapter 3).

6.4. Incorporating Climate Change into Event-Based Design Flood Estimates

Key messages

Changes in extreme rainfall are likely to represent the primary mechanism for increases in flood risk across most Australian catchments. This section provides information on how to adjust design rainfall estimates as well as temporal patterns, loss parameters, and sea level rise. Uncertainties are presented for each of the aspects of the design flood estimate for which climate change guidance is provided. The reader is referred to supporting guidance for sea level rise. Examples are presented in Book 1, Chapter 6, Section 6.

Event-based procedures are summarised in Book 4, Chapter 3, and as highlighted in that chapter, they generally take into consideration the following climate-related factors:

1. A design storm of a given AEP and duration, usually derived from published IFD data (Book 2, Chapter 2).

2. Temporal patterns to distribute the design rainfall over the duration of the event (Book 2, Chapter 5).

3. Spatial patterns to represent rainfall variation over a catchment (Book 2, Chapter 4).

4. Loss parameters that represent soil moisture conditions in the catchment antecedent to the event and the capacity of the soil to absorb rainfall during the event (Book 5, Chapter 5).

This list of climate-related factors is not necessarily exhaustive. For example, in low-lying (such as estuarine) catchments, the above is combined with information on sea levels that are influenced by both astronomical tides and storm surges (Book 6, Chapter 5). In the following sections, guidance is provided on accounting for climate change associated with each of the 4 aspects of event-based design flood modelling described above. The section closes with a discussion of the approach to estimating the epistemic uncertainty.

6.4.1. Intensity-Frequency-Duration Curves

For most Australian catchments, changes in extreme rainfall are likely to represent the primary mechanism for increases in flood risk with Wasko et al. (2024) identifying over 40 studies that quantify changes of extreme rainfall over Australia. For consistency with the Intergovernmental Panel on Climate Change (IPCC) projections, and to be representative of the climatic drivers of changes in moisture sources, a scaling approach is recommended whereby design rainfalls are factored at a rate proportional to global surface (land and sea) temperature increase.

The current IFD curves that are included in the 2016 IFD portal[1] were derived using historical data (Book 2, Chapter 3). The data from individual gauges varies, but a good estimate for the midpoint of the data period used in estimating the 2016 IFDs is 1961-1990. Figure 1.6.2 presents the latest Intergovernmental Panel on Climate Change (IPCC) temperature projections based on Shared Socioeconomic Pathways (SSPs) that cover a broad range of potential future development options often referred to as very low (SSP1-1.9), low (SSP1-2.6), medium (SSP2-4.5), high (SSP3-7.0) and very high (SSP5-8.5) emissions pathways. The best estimate for the mid-point of the data used for the generation of the 2016 IFDs is shaded. As global temperatures have risen since this period, design rainfall estimates require factoring to account for this temperature increase.

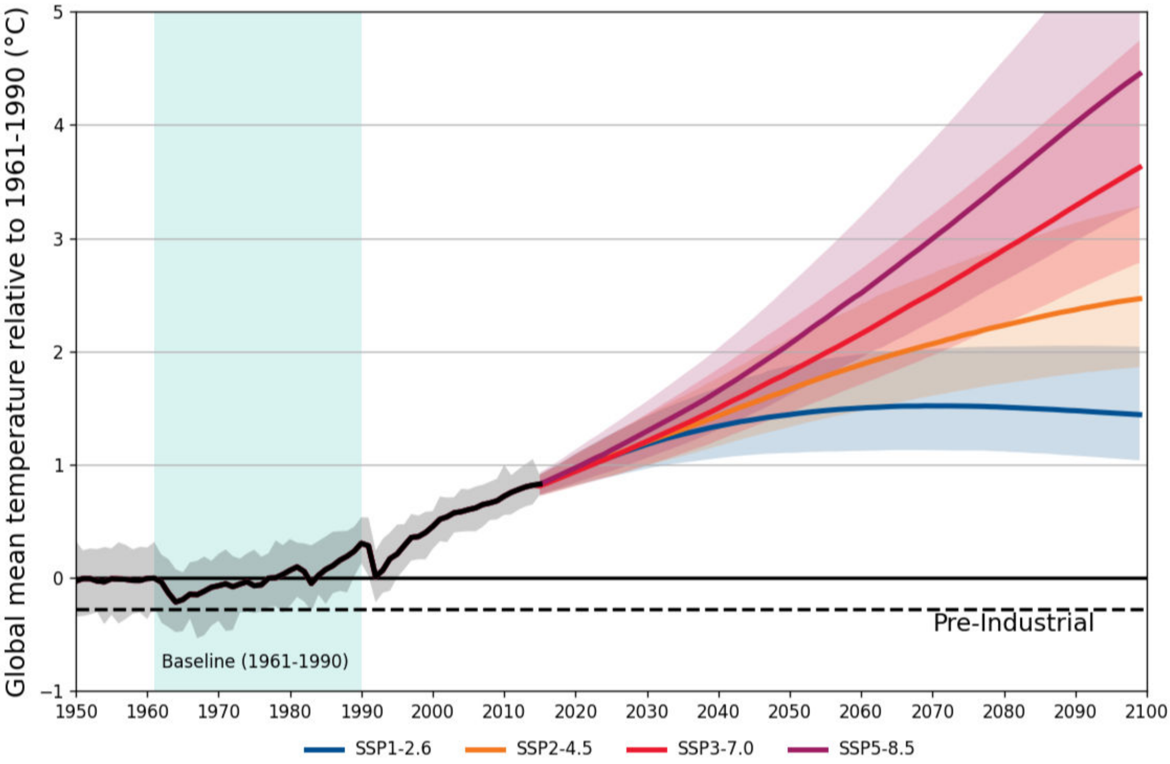

Figure 1.6.2. Projected temperature increases associated with AR6 socioeconomic pathways relative to 1961-1990 and their associated uncertainty[2]

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[1] http://www.bom.gov.au/water/designRainfalls/ifd/

[2] Figure based on Figure SPM.8 from the Summary for Policymakers (SPM) of the Working Group I (WGI) Contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (IPCC, 2021; Fyfe et al., 2021). Data can be obtained from the associated references.

To account for changes since the period represented by the IFD curves in the 2016 IFD portal, it is recommended that IFD information as well as estimates of the PMP should be adjusted using Equation (1.6.1) and the relevant rate of change in Table 1.6.1:

$$I_p = I \times \left(1 + \frac{\alpha}{100}\right)^{\Delta \mathrm{T}} \tag{1.6.1}$$

where

- I_p the projected (current or future) design rainfall depth or intensity
- α is the rate of change from Table 1.6.1
- I is the historical design rainfall depth or intensity (e.g. from the 2016 IFD portal or historical PMP estimates)
- ΔT is the most up-to-date estimate of global (land and ocean) temperature projection for the design period of interest and selected climate scenario relative to a baseline time period. When used in conjunction with the 2016 IFD curves the baseline is recommended to be the 1961-1990 period (see Table 1.6.2 and text below).

The rates of change in Table 1.6.1 apply to exceedance probabilities from the 1EY event through to the PMP and have been developed for application across mainland Australia and Tasmania. There is some evidence for heterogeneity in the rate of change across space as well as by event severity. However, there is insufficient information to quantitatively describe these differences, and/or the magnitude of difference was deemed to be small relative to the associated uncertainty. The information provided in Table 1.6.1 relates to storm durations for which most published evidence is available. Guidance on factors for use with burst durations between 1 and 24 hours is given in Appendix A. As pre-burst rainfalls are defined as a fixed proportion of the burst rainfall depth (Book 2, Chapter 5), these rates of change also apply to pre-burst rainfalls.

The differing rates of change with storm duration reflect the fact that the mechanisms that cause extreme rainfall at these 2 durations are often distinct. Note that short duration extremes are often embedded in longer duration extremes. It is possible that application of the scaling factors provided in Table 1.6.1 and Table 1.6.5 may yield inconsistencies in the resulting design rainfall frequency curves. Such inconsistencies are not unexpected given the uncertainties involved in their derivation. Accordingly, the IFD curves should be adjusted as minimally as possible to ensure the curve of one duration does not cross the curve of another.

Table 1.6.1. Recommended rates of change (α) and associated uncertainty derived in Wasko et al. (2024), presented per degree global temperature change (%/°C). The factors in this table are applicable for exceedance probabilities from 1EY up to and including the PMP and are designed for application across mainland Australia and Tasmania.

	≤ 1 hr	**> 1 hr and < 24 hr**	**≥ 24 hr**
Central (median) estimate (%/°C)	15	Interpolation zone (see Table 1.6.5)	8
‘Likely’ range (corresponding to ~66%[a] range) (%/°C)	7-28		2-15

[a] Consistent with terminology used by the IPCC the 66% range corresponds to an uncertainty range of +/- 33%.

To ensure consistency with IPCC projections and be representative of the climatic drivers of change in extreme rainfall, the rates of change in Table 1.6.1 are presented relative to global temperature changes. Hence, to adjust IFDs for climate change, global temperature projections ∆T are required. The current global temperature projections are provided in Table 1.6.2 are derived from the IPCC Sixth Assessment Report (AR6). An example application of Equation (1.6.1) is provided in Example 1a in Book 1, Chapter 6, Section 6.

A range of factors are likely to influence selection of SSP(s) that are specific to the design problem of interest. For more information on how to include SSP uncertainty as part of a holistic assessment of flood risk uncertainty, refer to Book 1, Chapter 6, Section 6. Users should seek the most up to date relevant guidance or information in relation to the selection of timeframes and climate scenarios.

Table 1.6.2. Global mean surface temperature projections (∆T) for four socio-economic pathways relative to 1961-1990. The 90% uncertainty interval is provided in parentheses[a]

Climate Scenario	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Current and near-term (2021-2040) (°C)	1.2 (0.9-1.5)	1.2 (0.9-1.5)	1.2 (0.9-1.5)	1.3 (1.0-1.6)
Medium-term (2041-2060) (°C)	1.4 (1.0-1.9)	1.7 (1.3-2.2)	1.8 (1.4-2.3)	2.1 (1.6-2.7)
Long-term (2081-2100) (°C)	1.5 (1.0-2.1)	2.4 (1.8-3.2)	3.3 (2.5-4.3)	4.1 (3.0-5.4)

[a]Projections adapted from the Summary for Policymakers (SPM) of the Working Group I (WGI) Contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)[b]. The projected temperature increases in the table above use a different baseline to the global warming levels referenced in relation to the Paris Agreement which uses a pre-industrial period (represented by the 1850-1900 period). There are approximately 0.3 degrees of global warming between the pre-industrial reference and 1961-1990, and this amount needs to be added to the temperatures in the above if comparing to the 1850-1900 period. The IPCC offers a range of summary projections information including in the assessment reports and the interactive atlas. We have selected the global climate projections from AR6 as they represent a balanced assessment of future global climate based on multiple lines of evidence, rather than a simple average of the global climate model output. This data is only available at the global level, not the regional level.

[ab] Refer to Table SPM.1 from the Summary for Policymakers (SPM) of the Working Group I (WGI) Contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC, 2021)

The IPCC AR6 projections use climate model simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) based on a range of assumptions including physical climate science, socio-economic factors and mitigation efforts. These projections are neither predictions nor forecasts but instead describe plausible scenarios that represent future climate uncertainty. It is noted that future Assessment Reports by the IPCC may potentially move away from the current SSPs. If a user wishes to design based on Global Warming Levels – the global temperature change relative to the pre-industrial period of 1850-1900 – then an adjustment for the additional warming of 0.3°C between 1850-1900 and 1961-1990 is required (see Example 1b). Further, it may be that IFD curves will be updated in the future. If a user has reason to believe a different baseline (refer Figure 1.6.2) is applicable to the adjustment of design rainfalls, then the warming since the baseline needs to be calculated by the user (see Example 1c). Readers should always refer to the latest global climate projections and Global Warming Levels.

The projections in Table 1.6.2 are provided up to 2081-2100. For projections up to the year 2300, the reader is referred to Section 4.7.1.2 in Chapter 4 of the IPCC AR6 Report[3], noting that for SSP2-4.5, SSP3-7.0 and SSP5-8.5, temperatures are projected to continue increasing beyond 2100. Although there may be interest in using projections beyond 2100 for flood designs with a long effective service and/or design life, the available evidence to

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[3] https://www.ipcc.ch/report/ar6/wg1/ (Lee et al., 2021)

support such projections is more speculative than that used to develop projections out to 2100. The defensibility of designing for specific climate change projections beyond 2100 is therefore questionable, and a more flexible and adaptive approach may be advisable. No formal guidance on adaptive approaches has yet been developed for flood design in Australia, but adaptive design generally involves building in flexibility to adapt to changing conditions. That is, rather than build a structure to withstand loading conditions as they might exist beyond 2100, structures with long service lives might be designed to cater for conditions over the time horizons described in Table 1.6.2, while also ensuring that the structure can be augmented in the future to cater for more severe conditions as necessary. A simple illustration of this concept is provided in Example 2 (Book 1, Chapter 6, Section 6).

6.4.2. Temporal Patterns

Evidence presented in Wasko et al. (2024) found that due to climate change, temporal patterns may become slightly more front-loaded with a greater proportion of the storm volume falling towards the start of the storm. While the shift towards more front-loaded storms based on the analysis of historical data is statistically significant, the magnitude of these changes is small and the impact of temporal pattern changes on design flood estimates may be of little practical significance, particularly for those systems where flood levels are largely dependent on flood volume.

Currently there is no published methodology for quantifying the effect of changing temporal patterns on design flood estimates, nor published literature on the implications on their impacts on design flood estimates. If a user believes their design flood estimate may be sensitive to small changes in the temporal pattern, a sensitivity analysis can be undertaken (Book 7, Chapter 9). This can be performed using a non-uniform sampling (or weighting) approach in either an Ensemble Event averaging (Book 4, Chapter 3, Section 2) or Monte Carlo scheme (Book 4, Chapter 3, Section 2) whereby temporal patterns are preferentially selected based on projected future changes. If Ensemble Event averaging is used, then it may also be possible to directly alter the shape of the temporal patterns.

The projected change can be assessed by applying a reduction in the percentage of the event duration at which 50% of the cumulative event precipitation total is reached. This reduction is to be applied relative to the global temperature change ΔT (Table 1.6.2) as per Equation (1.6.1). For storm durations less than or equal to 6 hours, this change is no greater than a 2.5% per degree global temperature change. For events between 6 and 24 hours in duration the reduction is no greater than 1% per degree global temperature change. For longer durations, the shift may be assumed to be zero. More detailed information on the variation and uncertainty in these factors can be found in Figure 9 in Visser et al. (2023).

6.4.3. Spatial Patterns

Although there is some evidence that climate change will influence spatial patterns of extreme rainfall, there are considerable uncertainties around such changes for localised regions. As such, there is insufficient justification for amending spatial patterns or areal reduction factors.

6.4.4. Loss Parameters

There is evidence that historical changes in antecedent moisture conditions – the expected conditions prior to an extreme rainfall event – have impacted on frequent flood peaks, with smaller proportional impacts for rarer events. The review of Wasko et al. (2024) found multiple studies that presented evidence of drying antecedent moisture conditions across

Australia, particularly in regions that are experiencing decreases in annual and/or seasonal rainfall. Ho et al. (2023) linked projected changes in soil moisture to loss model parameters, allowing for the projection of loss parameters in design flood estimation under climate change. Respecting that regional differences will exist due to the differential wetting/drying of the continent with climate change, particularly with greater drying projected in southern Australia, Table 1.6.3 presents rates of change per degree Celsius for the National Resource Management Regions clusters (Figure 2.5.7) (CSIRO and Bureau of Meteorology, 2015). These clusters are the same as those used for temporal patterns (Book 2, Chapter 5, Section 3) and can be obtained from the ARR datahub (Babister et al., 2016). As there is limited data for the Rangelands, a pragmatic solution is to apply the changes recommended for the East Flatlands and West Flatlands.

The rates of change for initial loss (IL) and continuing loss (CL) are generally positive (losses will generally increase with higher temperatures), which reduces the impact of increased rainfall intensities, particularly for frequent floods or for systems whose performance is dependent on the volume of a flood as well as its peak. While it is perhaps surprising that adjustment factors are applied to continuing loss, it needs to be recognised that the IL/CL model is a gross simplification of the governing catchment processes. For example, it ignores differences in the travel times of runoff response across the catchment, differences in partially saturated areas due to antecedent conditions, and spatial heterogeneity of soil properties. As such, it is to be expected that the tendency for soils to be drier in warmer conditions will impact on estimates of both initial and continuing loss.

To adjust the loss parameters for climate change, the rates of change can be applied as per Equation (1.6.1) relative to the 1961-1990 baseline, as this represents a similar data baseline for the derivation of loss parameters in Book 5, Chapter 3 (see Example 2). As these represent storm losses, if applied to bursts they can be applied with reference to Book 2, Chapter 5, Section 9. The uncertainty range represents pooling across individual sites, climate change projections, different climate models and bias corrections methods. Given this pooling, and the non-linear response of soil moisture to changes in rainfall and temperature, the uncertainty presented here is likely to underestimate the true uncertainty. A sensitivity analysis to these uncertainties can be undertaken following the methodology in Book 7, Chapter 9.

Table 1.6.3. Rates of change for initial loss (IL) and continuous loss (CL) parameters per degree global temperature change (%/°C) for Natural Resource Management Regions clusters (CSIRO and Bureau of Meteorology, 2015), adapted from Ho et al. (2023). The ‘likely’ range (corresponding to ~66% range) is presented in parenthesis. These rates of change should be applied relative to a 1961-1990 baseline global temperature date unless a reasonable alternative is justified

Natural Resource Management Cluster	IL (%/°C)	CL (%/°C)
East Flatlands, and West Flatlands, Rangelands, and Rangelands West	4.5 (2.0-7.1)	5.6 (2.5-8.7)
Murray Basin	3.1 (1.0-5.7)	6.7 (1.5-12.1)
Southern Slopes Mainland, and Southern Slopes Tasmania	3.9 (1.5-7.2)	8.5 (2.9-15.7)
East Coast North, and East Coast South	2.0 (0.6-4.3)	3.8 (1.1-8.0)

Natural Resource Management Cluster	IL (%/°C)	CL (%/°C)
Central Slopes	1.1 (0.4-2.2)	2.0 (-0.5-7.5)
Wet Tropics	0.8 (-0.4-2.0)	1.4 (-0.1-4.8)
Monsoonal North	2.4 (1.0-5.4)	4.4(3.1-9.5)

6.4.5. Sea Levels and Sea Level Interaction

There is significant evidence that sea levels are increasing and will continue to increase due to climate change. Acknowledging that sea level rise and changes in storm surges vary regionally, the reader is referred to the 4th Edition of the Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering (Harper, 2017) (and future updates) as well as their own jurisdictional guidance on changes in the sea level. The change in the sea level, jointly with a change in the extreme rainfall, can then be considered using the steps outlined in Book 6, Chapter 5, Section 5.

Changes to the interaction (or ‘joint probability’) between high sea levels (due to the combination of high astronomic tides and storm surges) and heavy rainfall events, remain poorly understood. The approach to calculating the joint probability of extreme rainfall and elevated sea levels described in Book 6, Chapter 5 does not account for possible changes in the interaction between those drivers. One approach to evaluate the importance of changes to the interaction between extreme rainfall and storm surge would be to conduct a sensitivity analysis on the dependence parameter recommended in Book 6, Chapter 5.

6.4.6. Increased Uncertainty Due to Climate Change

As discussed in Book 1, Chapter 6, Section 1, design flood estimates need to account for climate change and the associated increase in uncertainty. Epistemic uncertainties (due to lack of knowledge) affect:

- temperature projections, due to future emission pathways and feedbacks within the earth system, as described in Table 1.6.2
- future precipitation extremes for a given temperature change, as described in Table 1.6.1
- loss parameters, as described in Table 1.6.3.

Although not provided here, epistemic uncertainties also impact:

- sea level rise
- other inputs to the rainfall-runoff model, including temporal and spatial patterns
- rainfall-runoff transformation, recognising that potential changes to catchment properties (such as vegetation changes and/or bushfire) may mean that calibration of rainfall-runoff models to historic information may not reflect future conditions.

Each of these epistemic uncertainties affect the overall confidence in the design flood estimate. Epistemic uncertainties are not unique to the consideration of climate change. For example, IFD curves have inherent uncertainties associated with finite sample sizes. There are also other knowledge-based uncertainties associated with translating rainfall to estimates of runoff, flood level and velocity. When applied in the context of risk assessments, there are also uncertainties in estimating consequences (such as damages and/or loss of life) that reflect current and future exposure and vulnerability of assets and populations. It is recommended that approaches to characterising uncertainty associated with design floods should recognise that both climate change factors and non-climate change factors influence the design flood uncertainty. Various approaches for representing uncertainty within design flood estimation methods are provided in Book 7, Chapter 9.

6.5. Future Updates to the Climate Change Considerations

Key messages

While information in this update is the best available at the time of publication, more and better information will become available over the coming years. Future updates should consider the same approach of drawing on peer-reviewed science, considering multiple lines of evidence, synthesising these lines of evidence and publishing the results in a reputable peer-reviewed journal.

Climate change projections provided in this guidance are based on the review of the science by Wasko et al. (2024) and represent best-available information at the time of publication. The science review adopted a rigorous systematic review process, together with a meta-analysis to quantify the scaling relationships presented in Book 1, Chapter 6, Section 4. Information from multiple lines of evidence was sought, including the instrumental records (such as daily and sub-daily rainfall datasets and radar rainfall records) and modelling studies (including general circulation models and several classes of regional climate models together with statistical downscaling approaches).

It is recommended that future best practice updates of this chapter should consider:

- drawing on peer-reviewed studies in reputable scientific journals
- adopting a multiple-lines-of-evidence approach that recognises potential limitations with any single line of evidence
- synthesising available evidence using protocols that ensure rigour and avoid potential for biases
- ensuring that any synthesis is peer-reviewed and published in a reputable scientific journal.

6.6. Worked Examples

Key messages

This section comprises 4 worked examples. Examples 1a, 1b and 1c present a simple end-of-life design. They aim to familiarise the practitioner with the use of temperature projections in the context of design rainfall adjustment. The choice of climate scenario in these first examples is solely adopted for the purposes of demonstrating design rainfall adjustment.

Example 2 focuses on design flood estimation using adaptive management, presenting a use case that demonstrates how a practitioner could adopt climate scenarios in their design.

The user should also consider the decisions their modelling is informing and seek relevant jurisdictional guidance or information in relation to the consideration of climate change, including the selection of timeframes and climate scenarios.

The examples are:

1a - Design rainfall adjustment for a given emissions scenario.

1b - Design rainfall adjustment for a given global warming level.

1c - Design rainfall adjustment using a non-standard baseline.

2 - Adaptive management under uncertainty in the future climate.

Example 1a - Design rainfall adjustment for a given emissions scenario

This example presents a common use case where a practitioner wishes to estimate the impact of climate change on the existing 2016 IFDs for a time horizon corresponding to the end of the century (2081 to 2100 time horizon, Table 1.6.2). For this example, the practitioner requires an estimate of the 1% AEP 24-hour rainfall depth.

Using the 2016 IFD portal (Book 2, Chapter 3) the rainfall depth for the 24 hour, 1% AEP is 300 mm.

Table 1.6.1 provides an 8%/°C rate of change for a duration of 24 hours. The practitioner is testing the impact of the SSP2-4.5, which corresponds to a 2.4°C increase by the end of the century (Table 1.6.2) relative to the baseline adopted for the 2016 IFDs.

Using Equation (1.6.1) the factored design rainfall is:

$$300 \times \left(1 + \frac{8}{100}\right)^{2.4} = 361\mathrm{mm}$$

Example 1b - Design rainfall adjustment for a given global warming level

The Shared Socioeconomic Pathways (SSPs) used in the sixth Assessment Report by the IPCC are likely to be superseded. Global Warming Levels (GWLs), which are derived from climate models run using SSPs, may be used more widely in the future to describe temperature projections. GWLs are reported relative to the pre-industrial period which has a different baseline to that used in the derivation of the 2016 IFDs. This example presents an approach to estimating the impact of climate change on design rainfall using global warming levels.

For comparison, we follow Example 1a. A practitioner wishes to estimate the 1% AEP 24 hour rainfall depth for the end of the century (2081 to 2100 time horizon, Table 1.6.2). Here, the practitioner is testing a scenario under which the world will warm by 3.0°C[4] by the end of the century relative to pre-industrial levels.

Using the 2016 IFD portal (Book 2, Chapter 3) the rainfall depth for the 24 hour, 1% AEP is 300 mm.

Table 1.6.1 provides an 8%/°C rate of change for a duration of 24 hours. The data used to derive the IFD curves can be approximated to correspond to the baseline of 1961-1990, but Global Warming Levels are calculated from pre-industrial periods. Hence the additional

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[4] This value corresponds closely to the projected warming for SSP2-4.5 by the end of the century.

warming is 3.0°C-0.3°C = 2.7°C where 0.3°C is the difference between the pre-industrial period and the period used for derivation of the 2016 IFD curves.

Using Equation (1.6.1) the factored design rainfall is:

$$300 \times \left(1 + \frac{8}{100}\right)^{2.7} = 369\text{mm}$$

Example 1c - Design rainfall adjustment using a non-standard baseline

It is likely that IFD curves may be updated from time to time and hence a different baseline will be relevant. Furthermore, a practitioner may have reason to believe that a different baseline applies to the data for a particular region or location. This example presents how temperature projections can be adjusted to a non-standard baseline.

Following Example 1a, a practitioner wishes to estimate the 1% AEP 24-hour rainfall depth for the end of the century (2081 to 2100 time horizon, Table 1.6.2). Here however, the practitioner has estimated the 24-hour 1% AEP design rainfall using a record length from 1951 to 2020.

Table 1.6.1 provides an 8%/°C rate of change for a duration of 24 hours. The practitioner needs to choose an emissions scenario and chooses to test the impact of SSP2-4.5 which corresponds to a 2.4°C increase by the end of the century (Table 1.6.2) relative to the baseline adopted for the 2016 IFDs. But the temperature projections in Table 1.6.2 are estimated relative to 1961-1990. Hence the practitioner needs to check if there was additional warming between these 2 baselines.

There are several reputable sources of global temperature anomalies[5]. Examples include:

- Met Office, in collaboration with the Climatic Research Unit (CRU) at the University of East Anglia (UK).[6]
- Goddard Institute for Space Studies (GISS), which is part of the National Aeronautics and Space Administration (NASA) (USA).[7]
- National Climatic Data Center (NCDC), which is part of the National Oceanic and Atmospheric Administration (NOAA) (USA).[8]

Using the data from NOAA, the difference between the mean global temperature for the 1951-2020 period is approximately 0.2°C warmer than the 1961-1990 baseline baseline (i.e. 0.5°C above the pre-industrial baseline 1850-1900). The practitioner can proceed using the temperatures provided in Table 1.6.2 by adjusting for this increase. The long-term climate projected temperature increase is 2.4°C-0.2°C = 2.2°C above the new 1951-2020 baseline.

Using Equation (1.6.1), the factored design rainfall is:

$$300 \times \left(1 + \frac{8}{100}\right)^{2.2} = 355\text{mm}$$

Example 2 - Adaptive management under uncertainty around future climate

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[5] A summary is provided at https://www.metoffice.gov.uk/weather/climate/science/global-temperature-records ; with links provided at https://climate.metoffice.cloud/temperature.html.

[6] See also https://crudata.uea.ac.uk/cru/data/temperature/

[7] See also https://data.giss.nasa.gov/gistemp/

[8] See also https://www.ncei.noaa.gov/access/monitoring/global-temperature-anomalies

A local council is considering construction of a levee to protect an adjacent community from flooding. A range of options were considered to find a solution that best balances the trade-offs between construction costs and ongoing savings in avoided damages and flood hazards. It was decided that the levee should provide protection from 1% AEP flooding impacts.

In this example, SSP2-4.5 and SSP3-7.0 are adopted as the moderate and high-warming scenarios, respectively, and the SSP5-8.5 scenario is adopted to aid the stress testing of decisions under a lower risk tolerance. Although SSP5-8.5 is not consistent with expected emission trends (Schwalm et al., 2020), using this scenario in a suite is one method of considering the uncertainty in each of the relationships between emissions, temperatures and resulting climate impacts. That is, use of the SSP5-8.5 scenario is used here to notionally represent a plausible upper bound on the projected climate impacts.

In practice, given the deep uncertainties involved, it was decided to take an adaptive approach whereby the levee was initially designed to provide protection from 1% AEP flooding out to the mid-term (2041-2060) under the mid-range emission scenario (SSP2-4.5). The design incorporated additional capacity in the levee foundations, and an extended riverbank corridor width to allow for a wider and taller embankment. This feature could be added at a time in the future associated with a high-range emission scenario (SSP3-7.0) with consideration given to the very-high (SSP5-8.5) emission scenario.

Accordingly, designs were prepared to provide for 2 combinations of emissions scenarios and time horizons (SSP2-4.5 in the mid-term, 2041-2060, and SSP3-7.0 in the long-term, 2081-2100), with consideration given to SSP5-8.5).

A summary of the design inputs used to develop the adaptive approach is provided in Table 1.6.4 for an event with a critical duration of 24 hours and historical design rainfall from the 2016 IFD portal of 125 mm, with initial loss of 15.0 mm and continuing loss of 2.5 mm/hr.

Table 1.6.4. Design inputs factor for climate change for Example 2. Design inputs assume an event critical duration of 24 hours duration and historical design rainfall of 125 mm, with initial loss of 15.0 mm and continuing loss of 2.5 mm/hr

Design consideration	SSP2-4.5 (2041-2060)	SSP3-7.0 (2081-2100)	SSP5-8.5 (2081-2100)
Temperature increase (°C)	1.7	3.3	4.1
24 hr rainfall (mm)	$125 \times \left(1+\frac{8}{100}\right)^{1.7} = 142$	$125 \times \left(1+\frac{8}{100}\right)^{3.3} = 161$	$125 \times \left(1+\frac{8}{100}\right)^{4.1} = 171$
Initial loss (mm)	$15.0 \times \left(1+\frac{3.9}{100}\right)^{1.7}$ $= 16.0$	$15.0 \times \left(1+\frac{3.9}{100}\right)^{3.3}$ $= 17.0$	$15.0 \times \left(1+\frac{3.9}{100}\right)^{4.1}$ $= 17.6$
Continuing loss (mm/hr)	$2.5 \times \left(1+\frac{8.5}{100}\right)^{1.7} = 2.9$	$2.5 \times \left(1+\frac{8.5}{100}\right)^{3.3} = 3.3$	$2.5 \times \left(1+\frac{8.5}{100}\right)^{4.1} = 3.5$

6.7. Appendix

Table 1.6.5. Interpolated rate of change for rainfall depth with associated uncertainty range. Values have been interpolated from the values provided in Table 1 which was derived in Wasko et al. (2024). Rates of change are presented per degree global temperature change

(%/°C). The factors in this table are applicable for exceedance probabilities from 1EY up to and including the PMP and are designed for application across mainland Australia and Tasmania. If applied to the 2016 IFD curves these rates of change should be applied relative to a 1961-1990 baseline global temperature date unless a reasonable alternative is justified. Less information is available for rates of change for storm bursts between 1 and 24 hours, and hence estimates for these durations are obtained by a simple non-linear interpolation that represents the pragmatic interpretation of results obtained from Visser et al. (2021)

Duration	Rate of change (%/°C) and estimates of 'likely' range (corresponding to ~66% range) in parentheses.
1.5 hour	13.7 (6.1-25.6)
2 hour	12.8 (5.5-24.0)
3 hour	11.8 (4.7-22.0)
4.5 hour	10.8 (4.0-20.3)
6 hour	10.2 (3.6-19.2)
9 hour	9.5 (3.1-17.8)
12 hour	9.0 (2.7-16.9)
18 hour	8.4 (2.3-15.7)

6.8. References

Babister, M., Trim, A., Testoni, I., Retallick, M. 2016. The Australian Rainfall and Runoff Datahub, 37th Hydrology and Water Resources Symposium Queenstown NZ

Bates, B., McLuckie D.,Westra S., Johnson F., Green J., Mummery J., Abbs D. (2019). Climate Change Considerations in Australian Rainfall and Runoff, A Guide to Flood Estimation, 2019 Version 4.1, pp. 159-172

CSIRO and Bureau of Meteorology (2015), Climate Change in Australia, Projections for Australia's NRM Regions. Technical Report, CSIRO and Bureau of Meteorology, Australia. Retrieved from www.climatechangeinaustralia.gov.au/en [http://www.climatechangeinaustralia.gov.au/en].

Fyfe, J., Fox-Kemper, B., Kopp, R., Garner, G. (2021). Summary for Policymakers of the Working Group I Contribution to the IPCC Sixth Assessment Report - data for Figure SPM.8 (v20210809). NERC EDS Centre for Environmental Data Analysis, doi: 10.5285/98af2184e13e4b91893ab72f301790db.

Harper, B. (2017) Guidelines for responding to the effects of climate change in coastal and ocean engineering. Engineers Australia, National Committee on Coastal and Ocean Engineering.

Ho, M., Wasko, C., O'Shea, D., Nathan, R., Vogel, E., Sharma, A. (2023). Changes in flood-associated rainfall losses under climate change. J. Hydrol. 625, 129950.

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.

IPCC (2021). Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

Lee, J.-Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou, 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672, doi:10.1017/9781009157896.006.

Schwalm, C.R., Glendon, S., Duffy, P.B. (2020). RCP8.5 tracks cumulative CO 2 emissions. Proc. Natl. Acad. Sci. 117, 19656–19657. https://doi.org/10.1073/pnas.2007117117

Visser, J.B., Wasko, C., Sharma, A., Nathan, R. (2023). Changing Storm Temporal Patterns with Increasing Temperatures across Australia. J. Clim. 36, 6247–6259.

Visser, J.B., Wasko, C., Sharma, A., Nathan, R. (2021). Eliminating the “hook” in Precipitation-Temperature Scaling. J. Clim. 34, 9535–9549. https://doi.org/10.1175/JCLI-D-21-0292.1

Wasko, C., Westra, S., Nathan, R., Pepler, A., Raupach, T., Dowdy, A., Johnson, F., Ho, M., McInnes, K., Jakob, D., Evans, J., Villarini, G., and Fowler, H. (2024) A systematic review of climate change science relevant to Australian design flood estimation, Hydrol. Earth Syst. Sci. 28, 1251–1285. https://doi.org/10.5194/hess-28-1251-2024

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