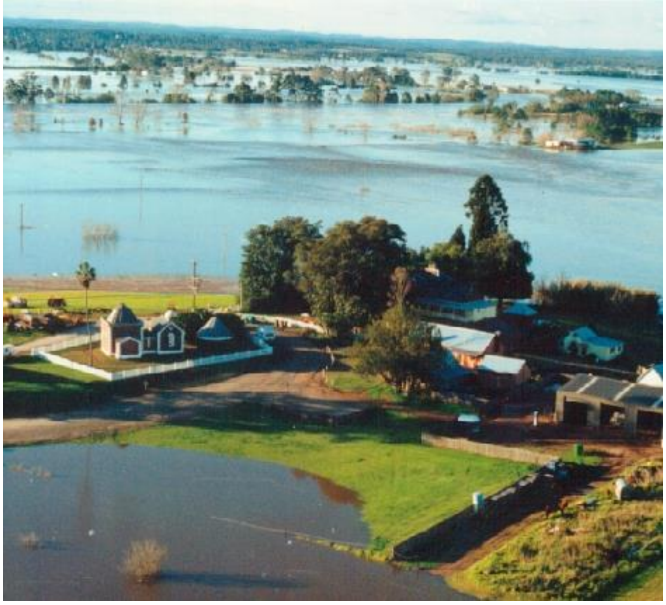

Australian Rainfall & Runoff

Revision Projects

PROJECT 3

Temporal Patterns of Rainfall

STAGE 3 REPORT

P3/S3/013

DECEMBER 2015

Australian Government

ENGINEERS AUSTRALIA
Water Engineering

AUSTRALIAN RAINFALL AND RUNOFF
REVISION PROJECT 3: TEMPORAL PATTERNS OF RAINFALL

STAGE 3 REPORT

DECEMBER, 2015

Project Project 3: Temporal Patterns of Rainfall	**AR&R Report Number** P3/S3/013
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Authors Melanie Loveridge, Mark Babister, Monique Retallick	**Verified by** James Ball

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ENGINEERS
AUSTRALIA
Water Engineering

Contractor Details

WMA Water
Level 2, 160 Clarence Street
Sydney NSW 2000

Tel: (02) 9299 2855
Fax: (02) 9262 6208
Email: wma@wmawater.com.au
Web: www.wmawater.com.au

wma water

FOREWORD

ARR Revision Process

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 current 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However, many of the practices recommended in the 1987 edition of ARR now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing 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. A recent and significant development has been that the revision of ARR has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The update will be completed in three stages. Twenty one revision projects have been identified and will be undertaken with the aim of filling knowledge gaps. Of these 21 projects, ten projects commenced in Stage 1 and an additional 9 projects commenced in Stage 2. The remaining two projects will commence in Stage 3. The outcomes of the projects will assist the ARR Editorial Team with the compiling and writing of chapters in the revised ARR.

Steering and Technical Committees have been established to assist the ARR Editorial Team in guiding the projects to achieve desired outcomes. Funding for Stages 1 and 2 of the ARR revision projects has been provided by the Federal Department of Climate Change and Energy Efficiency. 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.

Project 3: Temporal Patterns of Rainfall

Temporal patterns for design rainfall bursts at present are based on the Average Variability Method (AVM); an approach first proposed by Pilgrim and Cordery (1975) for estimating the temporal pattern of rainfall in the most intense burst of rainfall within a storm event.

This approach is known to result in storm bursts that have higher temporal correlations than exist in real storm events. This impacts on the estimation of flood flows due to the influence of the temporal pattern on the shape of the hydrograph; Ball (1994) showed that the rainfall temporal distribution significantly influenced the magnitude of the peak flow and more particularly the shape of the hydrograph. Furthermore, the validity of the assumption that an AVM pattern transforms the rainfall frequency to the flood frequency is unknown and untested.

Finally, there are many problems where the storm volume is significant and hence there is a need to consider not only the temporal pattern of the peak storm burst during an event but also the temporal pattern of rainfall prior to and post the peak burst of rainfall; a problem which has been discussed by Phillips (1984) and Rigby et al. (2003).

M K Babister

James Ball

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

ARR REVISION PROJECTS

The 21 ARR revision projects are listed below:

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	**Temporal pattern of rainfall**	**2**
4	Continuous rainfall sequences at a point	1
5	Regional flood methods	1
6	Loss models for catchment simulation	2
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people	1
11	Blockage of hydraulic structures	1
12	Selection of an approach	2
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	Two-dimensional (2D) modelling in urban areas.	1
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	Risk assessment and design life	2
21	IT Delivery and Communication Strategies	2

ARR Technical Committee:

Chair:	Mark Babister, WMAwater
Members:	Associate Professor James Ball, Editor ARR, UTS
	Professor George Kuczera, University of Newcastle
	Professor Martin Lambert, University of Adelaide
	Dr Rory Nathan, Jacobs
	Dr Bill Weeks
	Associate Professor Ashish Sharma, UNSW
	Dr Bryson Bates, CSIRO
	Steve Finlay, Engineers Australia

Related Appointments:

ARR Project Engineer:	Monique Retallick, WMAwater
ARR Admin Support:	Isabelle Testoni, WMAwater

Project Overview

The Stage 3 ARR revision Project 3: Temporal Patterns for Rainfall report consists of four major components of work. Each component has been reported in a separate part of the document but may use data or techniques described in earlier part. Each part is defined here with a brief description:

1. *Development of an events database* - this involves the extraction of storm events from each suitable pluviograph station across Australia.
2. *Analysis of pre-burst rainfalls* - this defines the magnitude and distribution of pre-burst to burst ratio across Australia and investigates any trends in the data (in relation to event severity and duration).
3. *Preliminary testing of temporal pattern ensembles* - this involves extracting and testing temporal pattern ensembles using a number of sampling techniques to extract events from the national events database and a number of event types (i.e. burst, complete storm and pre-burst), within a design environment.
4. *Areal temporal patterns of rainfall* - this describes the development and testing of areal temporal patterns for a range of AEPs, durations and catchment areas.

PROJECT TEAM

Project Team Members:

Mark Babister

Melanie Loveridge

Monique Retallick

Isabelle Testoni

Peter Brady

Peter Stensmyr

Melissa Adam

Other Contributors:

Erin Askew

Michelle Visser

Lovdeep Singh

LIST OF ORGANISATIONS WHO PROVIDED DATA AND ASSISTANCE

Australian Bureau of Meteorology

WMAwater (NSW)

Australian Rainfall & Runoff

Revision Projects

PROJECT 3: PART 1

Development of an Events Database

STAGE 3 REPORT

ENGINEERS
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Water Engineering

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1. Introduction

The report documents the first part of Australian Rainfall and Runoff Revision Project 3: Temporal patterns of Rainfall project (ARR revision Project 3). The aim of ARR Revision Project 3 is to develop new design event temporal patterns for use in flood estimation. The objective of Part 1 of the project is to create a national storm events database that can be used to develop the temporal patterns. The events database (as it will be called herein) contains storm events from the BoM quality controlled pluviograph database (developed as part of Australia Rainfall and Runoff Revision Project 1: Development of Intensity Frequency Duration data across Australia). This events database provides the potential to extract ensembles of temporal patterns based entirely on real storms, without the need for significant scaling or filtering except for the most data sparse regions. In addition, a flexible framework was developed so that it is possible to do this on a burst or complete storm basis.

A number of inputs are required for design flood estimates; including rainfall depths, temporal and spatial patterns and rainfall losses. After the rainfall depth, the temporal pattern of rainfall has the biggest influence on the flood estimate. The temporal patterns are also one of the last inputs to be considered in the ARR revision projects. Current practice (as specified in ARR 1987, Pilgrim 1987) uses a single burst Average Variability Method (AVM). These patterns can to bias flood estimates and are often unsuitable for volume-sensitive systems. Given the importance of temporal patterns in the design process, this stage of the study develops a flexible event database that is suited to both burst and storm event extraction using any given sampling method, for a specified site of interest across Australia.

The rest of this chapter discusses the current design event approach and other studies that have generated alternative design events since. The remaining chapters of the report are summarised as follows:

- Chapter 2 outlines data available for the study.
- Chapter 3 describes the national events database developed for this study, including a detailed account of how events were extracted from rainfall time series data. The algorithm described in this chapter is designed to reproduce the manual based approach used in ARR Project 6.
- Chapter 4 explains how ensembles can be sampled from the national events database, beyond simple location or region criteria.
- Chapter 5 covers the conclusions.

1.1. Background

1.1.1. Current Practice

Average Variability Method

Temporal patterns for design rainfall bursts that are currently recommended in ARR 87 are based on the Average Variability Method (AVM), first proposed by Pilgrim and Cordery (1975). At present, there is a single temporal pattern for each zone and duration with 2 AEP categories. The AVM method works by finding a burst rainfall event for a given duration and zone, then ranking each period within the burst (based on the rainfall depth). The rainfall depth is then transformed into a percentage of the total burst rainfall depth. The process is repeated for many bursts, before the average rainfall percentage (across all bursts) is calculated for each rainfall period (weighted towards larger events). The averaged pattern then becomes the design rainfall burst temporal pattern for that zone and duration.

The AVM patterns recommended in ARR 1987 were derived using pluviograph stations with more than 20 years of data. The number of bursts used to derive the average pattern in each zone was equal to the number of station years, with a cap of 301 rainfall bursts per zone. Rainfall bursts were filtered, but filtering of the temporal patterns was recommended in ARR 1987 to remove rarer internal bursts, though in practice this step is often neglected.

Disadvantages of the AVM

The AVM method is known to result in unrealistic rainfall temporal patterns, which contain higher temporal correlations than real burst rainfall events. This ultimately has an impact on the design flood estimates; this was proven by Ball (1994) who showed that the rainfall temporal pattern had a direct influence on the shape of the hydrograph and to a lesser extent, on the peak flow magnitude.

1.1.2. Temporal Pattern Techniques

Since the release of ARR 1987 there has been a myriad of temporal patterns generated for various reasons. The methods used for developing patterns include completely stochastic methods, such as DRIP (Heneker, 1999), methods which generate patterns by sampling actual pattern information example Hoang et al (2002), the AVM patterns developed for extreme storms (Nathan, 1999) and Varga (2009), or they can sample actual patterns either from a single pluviograph record, such as the RORB temporal pattern extractor tool (Laurenson, 2010), or from records within a region, such as Melbourne Water’s (Heron, 2010). The use of actual patterns has generally been restricted to the use of bursts because they are much easier to scale, however, if they are filtered they can no longer claim to represent observed burst events.

1.1.3. Event Definitions

ARR Project 6 required the derivation of a complete storm definition in order to estimate values of initial and continuing losses. Rainfall bursts were initially identified using a partial series with the threshold set so that the number of bursts was equal to the years of concurrent streamflow and pluviograph data for any given catchment.

Following the selection of the bursts, the complete storm events were derived manually on a subjective basis. Events were not allowed to overlap with each other, and when this occurred the event with the rarer critical burst period was kept. Some general rules were followed, however these could not always be met so a compromise needed to be made. The criteria adopted are as follows:

- Start and end times set to 9:00 am.
- Start time set to capture the beginning of the storm; being approximately 12 hours with minimal rainfall.
- End time set to when the streamflow had effectively ended, i.e. when the flow was a few percent of the peak flow.

2. Available Data

2.1. Rainfall Data

The current study is based on pluviograph data for the BoM quality controlled pluviograph database, containing 2280 stations with more than 8 station years. Of these, 754 are owned by the BoM and the other 1526 are owned by other data agencies throughout Australia. This data was provided by the BoM, who undertook quality controlling to identify suspect data, such as missing data, accumulated totals and time shifts (Green et al. 2011). All station data was provided as time series data sampled at a 5 minute time step. In addition to the rainfall depths, each data point had a quality code indicating the quality of the data. Figure 2-1 below depicts the geographical distribution of the pluviographs across Australia. Each station is represented as a circle, with the size of the circle indicating the record length of the station. This gives a broad indication of where there is ample data available and where data is sparse. The same dataset is shown at state level, for New South Wales (NSW) as found in Figure 2-2.

Figure 2-1: Pluviograph stations record lengths

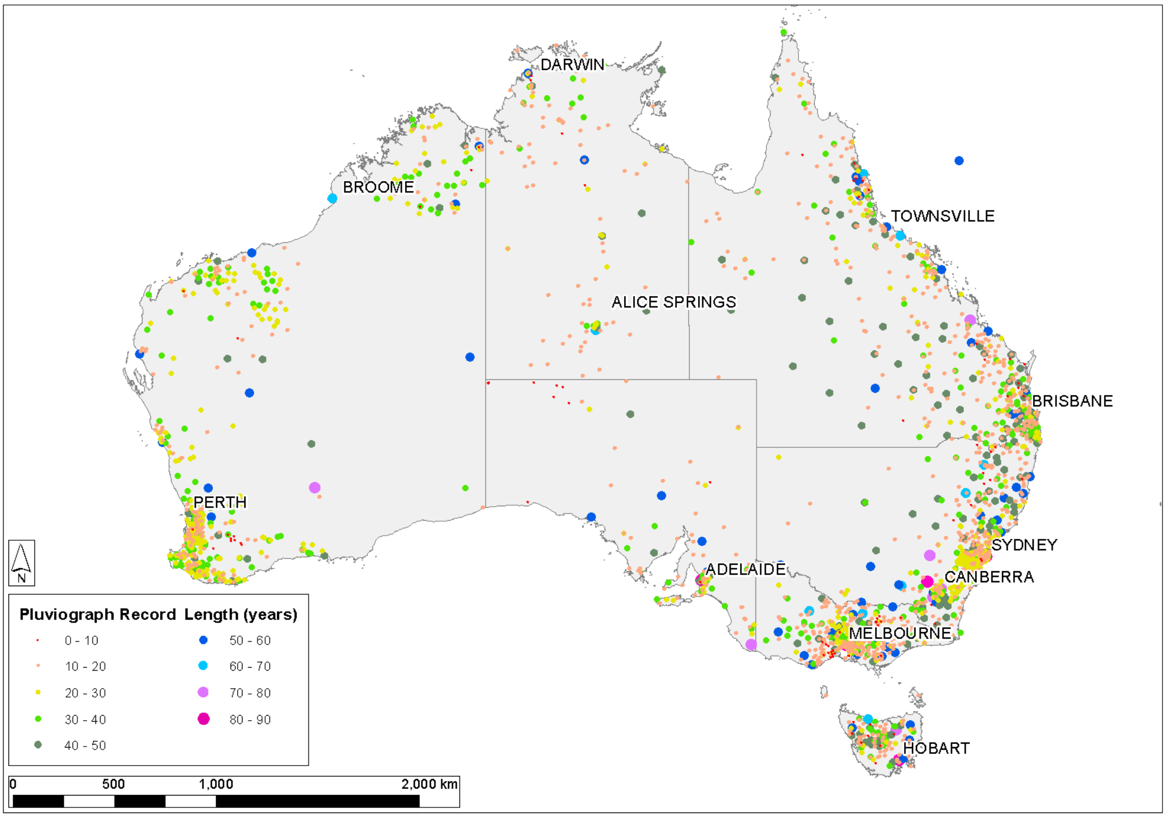


Figure 2-2: Pluviograph stations used throughout New South Wales, with record lengths indicated

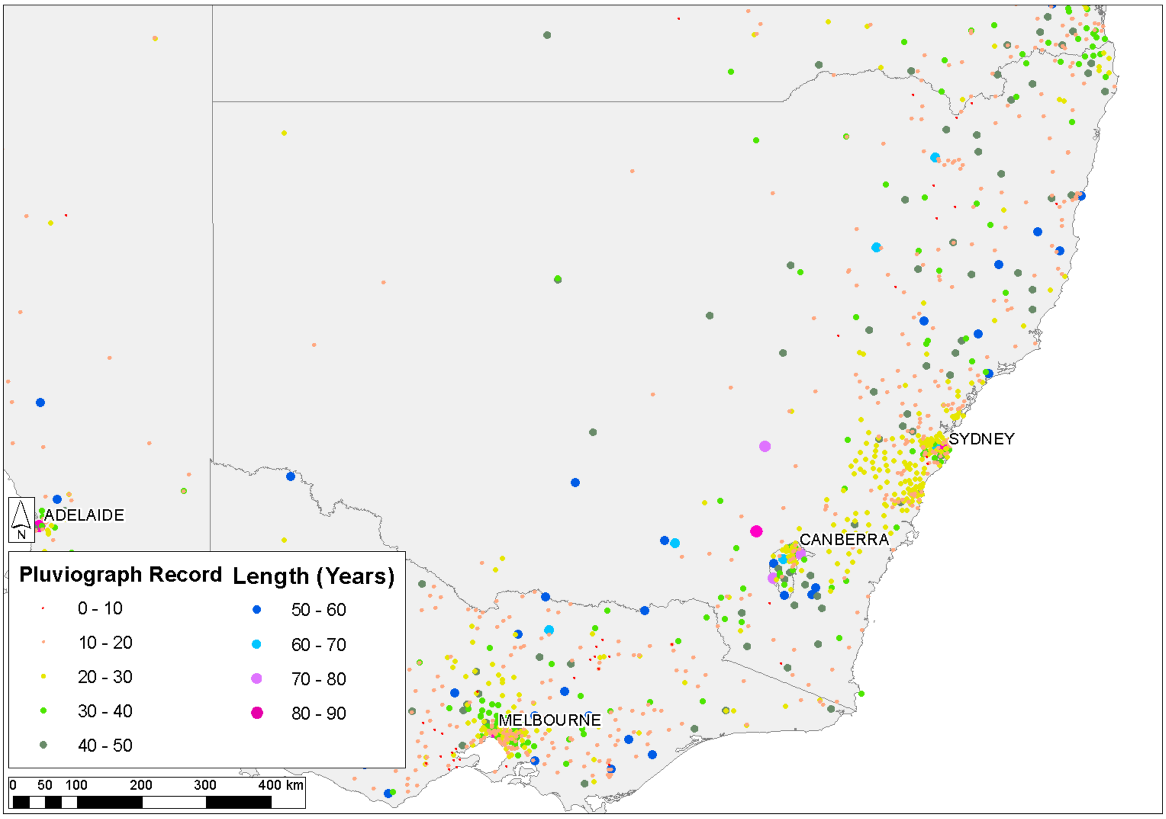


Figure 2-3 below shows a histogram of the record length for all stations. The average station record length is 25 years, with a combined record length of 57,000 years. Figure 2-4 shows the number of stations recording in each year, which peaked around 1995 to 2005. The number of stations drops dramatically after 2010 because it is a measure of the data used from the BoM pluviograph database and not the actual number of stations recording in any given year. While this may provide a rough idea of the data availability, this is not indicative of the data available to use; the effective station years is unknown due to missing data and other quality issues.

Figure 2-3 Histogram of the record lengths for each pluviograph station

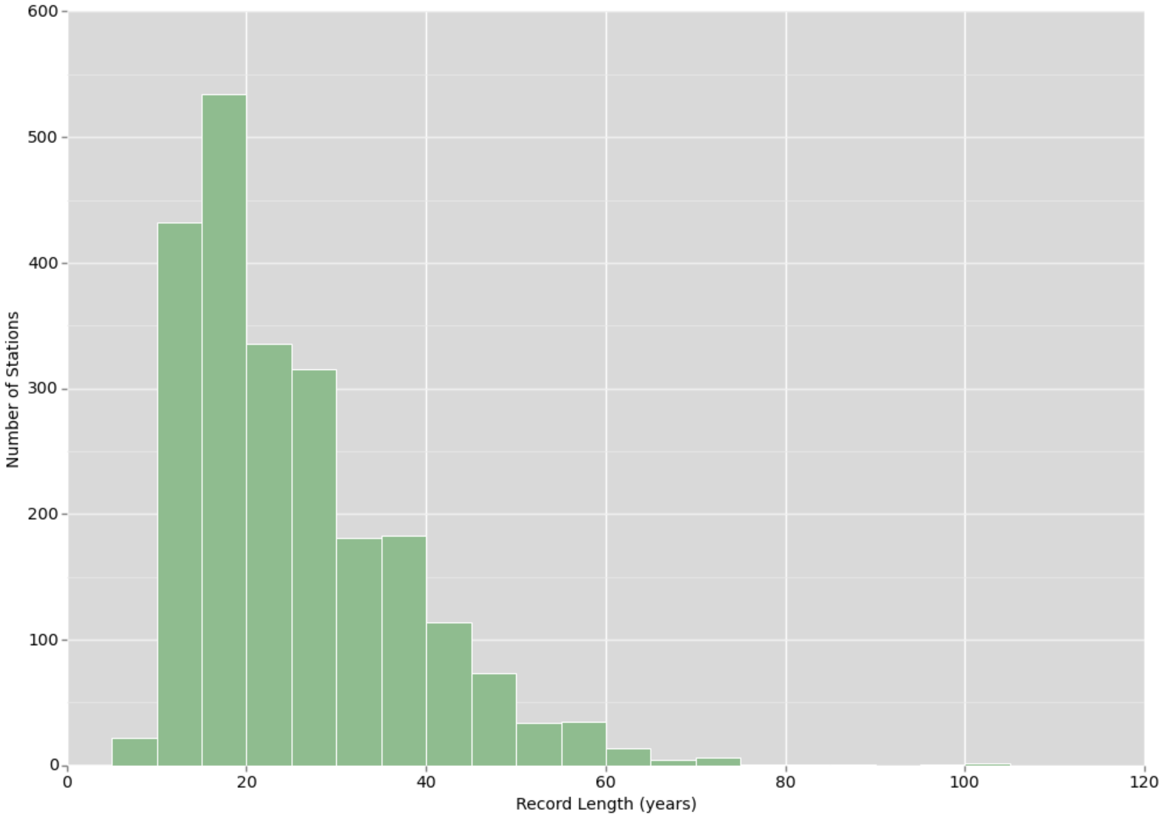
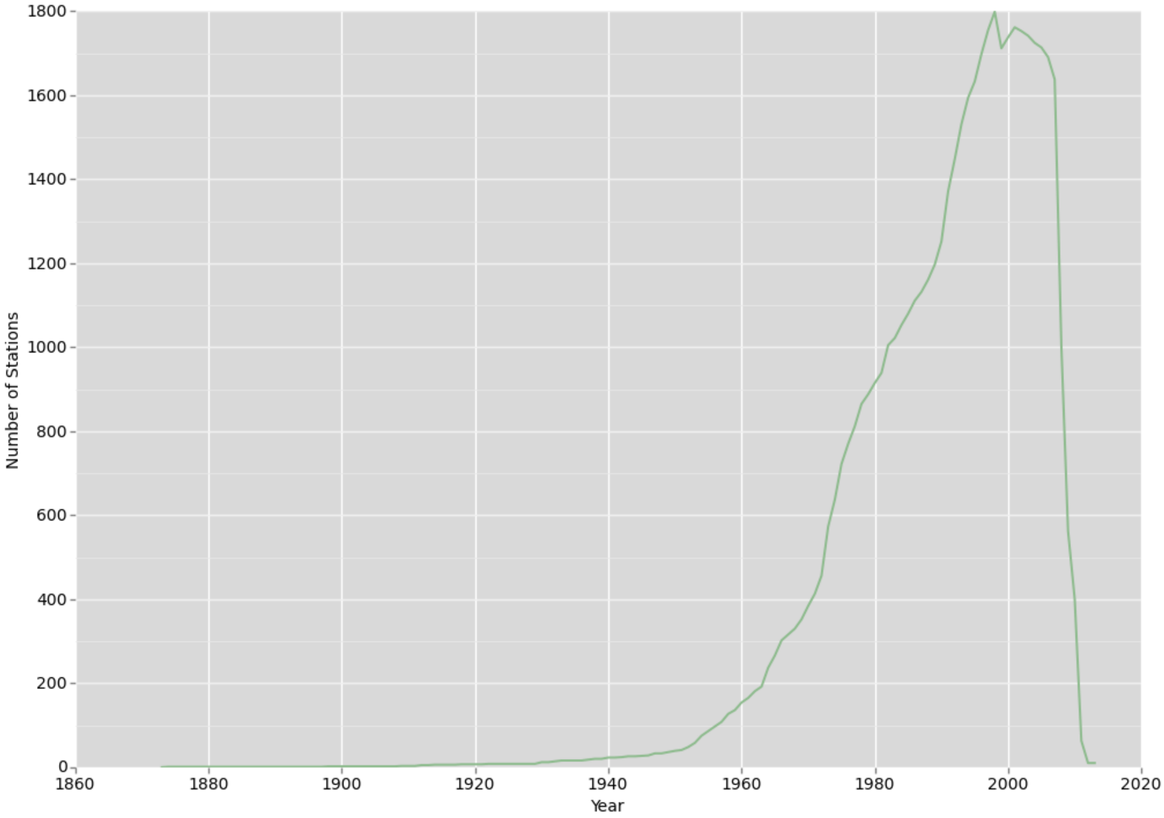


Figure 2-4 Number of pluviograph stations recording in any specific year, since records began



As shown in Figure 2-1 the highest density of pluviograph stations are typically found along coastal areas of Australia (around key population centres); more specifically, these areas include the east and south-east coast of Australia, Tasmania, and south-west Western Australia. In Figure 2-2, the pluviograph stations are seen to be clustered around urban areas, such as Sydney, Wollongong, Melbourne and Canberra. In general, the closer to the centre of Australia, the less data is available; with the exception of Alice Springs. It is important to note the lack of pluviograph stations in central Western Australia, the lack of sufficient data causes scaling issues in this region.

2.1.1. Data Quality

Pluviograph data is not only provided with depths, but also with quality codes related to the quality of a given point, with a substantial amount of quality controlling being carried out by the BoM, as a part of ARR revision Project 1: Development of Intensity Frequency Duration Information across Australia. One of the key issues flagged were interpolated data points, along with other issues such as 24 hour periods of rainfall that are vastly different to surrounding stations.

Some of the key concerns when undertaking a study using a single pluviograph station are that there is a long period of record (preferably longer that 30 years) and only a small percentage of missing data. However, for studies that pool data together, record length is no longer an issue; rather, the quality of the data is a key issue (particularly having minimal interpolated data points).

Events with uniformally disaggregated periods of rainfall are not desirable; however, if the disaggregated period only represents a very small portion of the storm it may be acceptable. The issue is complicated by the fact that continuous time series data collected from some agencies had a coarser time step resulting in short periods of uniform rainfall. This becomes an issue if the rainfall depth in two coarser periods is the same, but appears to be an aggregated period, rather than two consecutive periods of the same depth with a coarse resolution.

It was however necessary to disregard storms that appear to have been uniformally disaggregated, though short periods of uniformally disaggregated data could probably be accepted where they represent a very small component of a long storm.

2.1.2. Other Considerations

Pluviograph stations have improved over time with data being recorded at a higher resolution. A modern tipping bucket rainfall gauge records the time at which sufficient rainfall has accumulated in the tipping bucket for a tip to occur. Data used in the current study is collected using different techniques and sampled at 5 minute intervals.

This allows an in-depth characterisation of the temporal pattern for all the events in a record, but also comes with some issues. Small amounts of rain can be hard to detect, as rain is only detected when it goes above a threshold (for example 0.1 mm). For example, if 0.09 mm of rain falls over an area, then a few hours later there is a small rainfall, it will get registered as 0.1 mm for that 5-minute increment (assuming no evaporation occurs). However, the effects of this should be small in practice. While this volume of rainfall is not important for a pattern it is important for determining when a storm starts/finishes.

Another issue with the data is the loss of resolution in the data set when it is discretised into 5 minute increments. There is a chance that a short, intense burst will be distributed over two intervals. For example, a burst of rainfall occurring between the time of 12:09 and 12:11 contains 14 mm of rainfall. With the discretisation of the rainfall data into 5 minute increments, this rainfall is disaggregated into two time intervals of 8 and 6 mm. While this problem was recognised, there is no way to adjust for this problem without access to the original pluviograph trace or records; this however, is impractical for such a large dataset.

In addition, several other issues with the data quality were found. Some records contained significant periods of missing data. There were also periods of interpolated data, where several data points were indicated as interpolated from a later point, presumably at the end of an event. Since this report is concerned with the temporal distribution of rainfall within the storm, events where a significant part of the rainfall was interpolated were filtered out before further analysis. There were also sections where the rainfall was uniform over many intervals within an event, indicating that the data points were interpolated even though the quality control value did not specify that to be the case. Since storms generally do not have uniform rainfall, events that had a significant part of their total rainfall depth occurring in consecutive identical intervals were also filtered out. In addition to this, it is worth keeping in mind that older pluviograph records will generally be of worse quality, due to improvements in technology.

2.2. Intensity Frequency Duration Data

As part of the current revision of ARR, the BoM undertook a revision of the Intensity Frequency Duration (IFD) data (BoM 2013 IFD, released in July 2013), which superseded the previously derived IFDs from 1987. This 2013 IFD data was derived using the most intense rainfall depths. Improvements from the previously derived IFDs include the use of more rainfall gauges throughout Australia (regardless of ownership) with additional data being collected since 1983, and more up-to-date statistical techniques (Green et al. 2012). This study, therefore, used the BoM 2013 IFD data to extract design depths at each pluviograph station.

3. Development of a National Events Database

3.1. Overview

The national events database contains storm events from each pluviograph station in the BoM's quality controlled database; which includes those in the BoM's network, along with other data agencies (both public and private). Also included in the database are statistics of each storm event, including the storm loading (i.e. front, middle or back loaded), critical burst duration and rainfall depth. This database allows for pre-burst rainfall analyses to be conducted, the extraction temporal pattern ensembles, or investigation of regional trends in storm events.

The methods used to extract these storm events are briefly outlined in a flowchart in Figure 3-1 Flowchart of the process used to extract events from a continuous rainfall time series; as applied for the events database and further detailed in the following sections. While the process may be broken into smaller parts, each component is undertaken consecutively for each event, before moving onto the next event until the end of the record is reached. The entire process is then repeated for each pluviograph station and for each standard duration; each of the standard durations can be seen in Table 3-1. Following the definition of a complete storm, the events are grouped according to the critical burst duration; the range of each critical duration bin can also be found in Table 3-1.

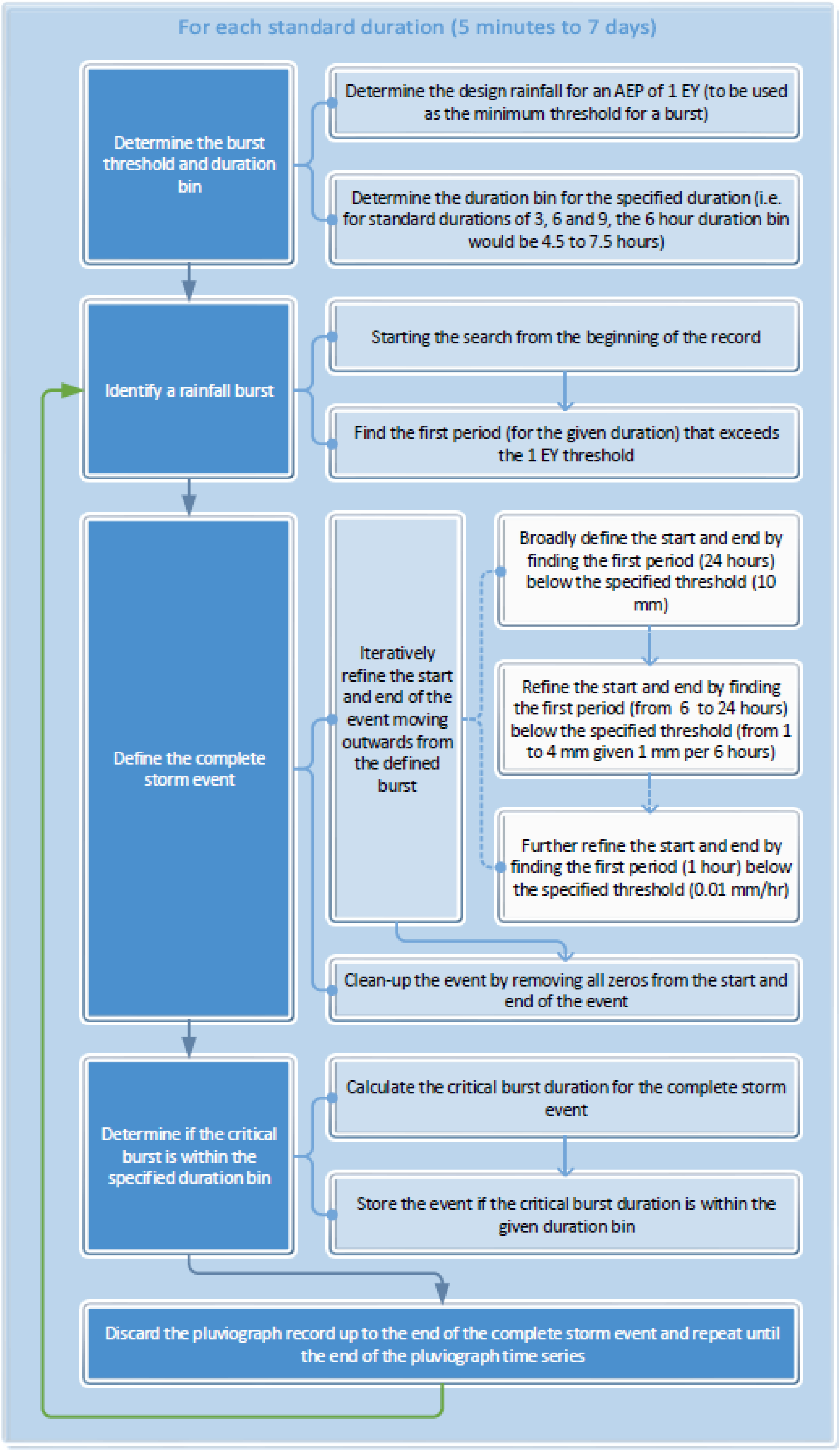
The key steps in the determination of storm events are as follows:

1. Find the first burst window (for a specified duration) above the 1 Exceedance Per Year (EY) design rainfall threshold (using the BoM 2013 IFD data),
2. Define the storm event surrounding the rainfall burst by iteratively refining the start and end of the event,
3. Determine whether the critical burst of the storm is within the specified duration bin; storing if the event is suitable for the given duration, and
4. Starting from the end of the previously defined event, repeat these steps until the end of the pluviograph record.

Table 3-1 Categorisation of Standard Durations & Bin Ranges

Standard Durations			**Critical Duration Bin Range**	
In Minutes	*In Hours*	*In Days*	*Minimum Critical Curation (hours)*	*Maximum Critical Duration (hours)*
5			0.075	0.125
10			0.125	0.208333333
15	0.25		0.208333333	0.375
30	0.5		0.375	0.75
60	1		0.75	1.5
120	2		1.5	2.5
180	3		2.5	3.75
270	4.5		3.75	5.25
360	6		5.25	7.5
540	9		7.5	10.5
720	12	0.5	10.5	15
1080	18	0.75	15	21
1440	24	1	21	30
2160	36	1.5	30	42
2880	48	2	42	60
4320	72	3	60	84
5760	96	4	84	108
7200	120	5	108	132
8640	144	6	132	156
10080	168	7	156	>

Figure 3-1 Flowchart of the process used to extract events from a continuous rainfall time series; as applied for the events database



3.2. Rainfall Burst Identification

Bursts, for a specified duration and pluviograph station, are first identified before the complete storm surrounding the burst is determined. Bursts are defined as a period of rainfall exceeding a specified rainfall depth. In this study, the rainfall threshold is taken as the 1 EY 2013 IFD's depth for the specified duration and pluviograph location. Beginning at the start of the record, the pluviograph record is successively searched to find the first rainfall period above the minimum rainfall threshold. The complete storm is then defined before the search begins again at the end of the previously defined complete storm event, or until the end of the pluviograph record.

This process is not carried out on all durations; rather the process is repeated for a range of discrete durations (see standard durations in Table 3-1. For this reason, some of the more frequent burst events may not be selected as the rainfall depths for the discrete durations fall below the 1 EY design rainfall depth, whilst one of the durations between these discrete durations contains a depth above the 1 EY design rainfall depth. For instance, a burst event may be above the 1 EY thresholds between the 7 and 8 hour durations, however if the burst does not exceed the 1 EY design rainfall depth for the standard durations of 6 and 9 hours the burst event will not be selected.

3.3. Complete Storm Definition

Many studies use simplistic start/end criteria where an event is classified as a period surrounded by a so called 'dry' period that is essentially a fixed period below a given threshold. Occasionally, another criteria is added, which includes shorter periods that exceed the intensity threshold in any given increment. The complete storm definition in this study is similar to previous studies (Rahman *et al.* 2001, Hill *et al.* 2014) with one key difference, being that either two or three criterion were used to define the complete storm event. Two event definitions were derived: the first was an initial trial that was compared to ARR Project 6 complete storm events and further refined to create the second event definition. Both definitions will be defined in more detail in the following two sections.

3.3.1. Initial Definition

The first complete storm definition used two criterion to iteratively refine the complete storm event. The first criteria is a period of rainfall, equal in length to the specified duration (given a minimum of 3 hours and a maximum of 24 hours) and an average rainfall intensity of 0.5 mm/h. The second criteria is used to more precisely define the start and end of the complete storm event, with a 'dry' period considered as a 1 hour period with less than 0.01 mm/h. With these criteria, the complete storm event is determined using the following steps:

- A burst rainfall period is identified as a period above the 1 EY design rainfall depth (see previous section).

- Moving outwards from the end of the burst event to find the first period that meets the first criteria, both for the start and the end of the event.
- Moving outwards from the point where the first criteria stopped (i.e. at the end of the 'dry' period with less than 0.5 mm/h) to find the first period that meets the second criteria, both for the start and the end of the event.

Given that these events will ultimately be used in a design environment, the extracted events need to be consistent with those used to derive other design inputs; form instance, complete storm event definition used to derive initial loss values as a part of ARR revision Project 6: Loss Models for Catchment Simulation, the same events database (and event definition) is adopted for ARR revision Project 2: Spatial Patterns of Rainfall (Stensmyr et al, 2014), and the bursts are extracted in the same manner as ARR revision Project 1: Development of Intensity-Frequency-Duration information across Australia (Green et al, 2012).

The biggest limitation for the comparison between this project and ARR Project 6, is that Project 6 events were derived subjectively by expert hydrologists, whilst this project required an automated algorithm due to the volume of data. Other minor differences included ARR P6 using ARR 1987 adjusted IFD data and start/end defined by 9:00 am. Regardless, value can still be made from the comparison; therefore the events derived in this study were plotted against the equivalent events from ARR Project 6. Three catchments from ARR Project 6 were investigated, including Toomuc Creek (Victoria), Yates Flat Creek (Western Australia) and Spring Creek (Queensland).

From the comparison it was found that the majority of events were reasonably well defined (as illustrated in Figure 3-2), with about 10% of the events found to be inconsistent. The events that were deemed to be inconsistent with ARR Project 6 events were generally found to be much shorter (examples Figure 3-3, Figure 3-4 and Figure 3-5). Most of the events with inconsistencies were missing rainfall after the rainfall burst (demonstrated in Figure 3-4) which may only be a problem with volume sensitive catchments. In some cases, however, the rainfall prior to the burst was overlooked (as shown in Figure 3-3). On some occasions these inconsistent events contained a reasonable amount of rainfall (as illustrated in Figure 3-5). This could lead to large biases in design flood estimates, due to inconsistencies between the events and initial losses.

Interestingly, the majority of the events that were too short were more frequent events, with a 20 % AEP or more frequent. The catchment in south-west Western Australia (Yates Flat Creek) had the most inconsistent events, possibly showing that climate drivers in this region may not produce well defined events.

Figure 3-2 Comparison of Project 3 (initial definition) and Project 6 derived events – consistent events

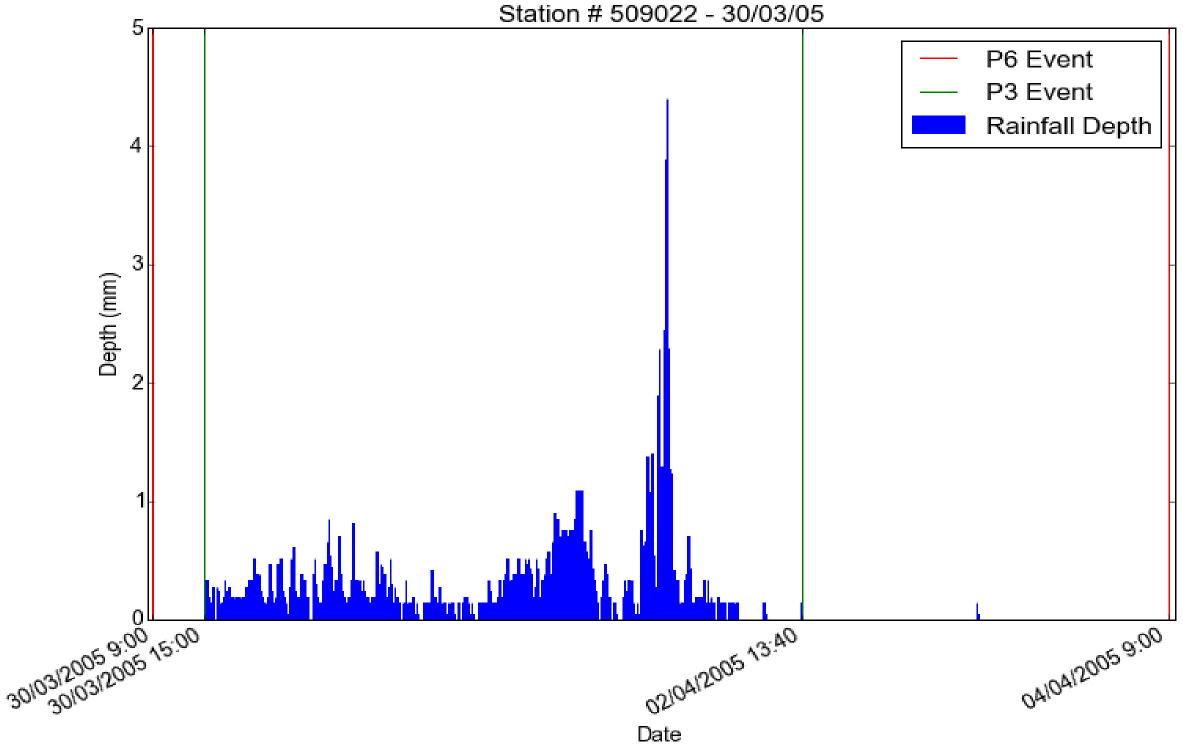


Figure 3-3 Comparison of Project 3 (initial definition) and Project 6 derived events – missing period of rainfall prior to event

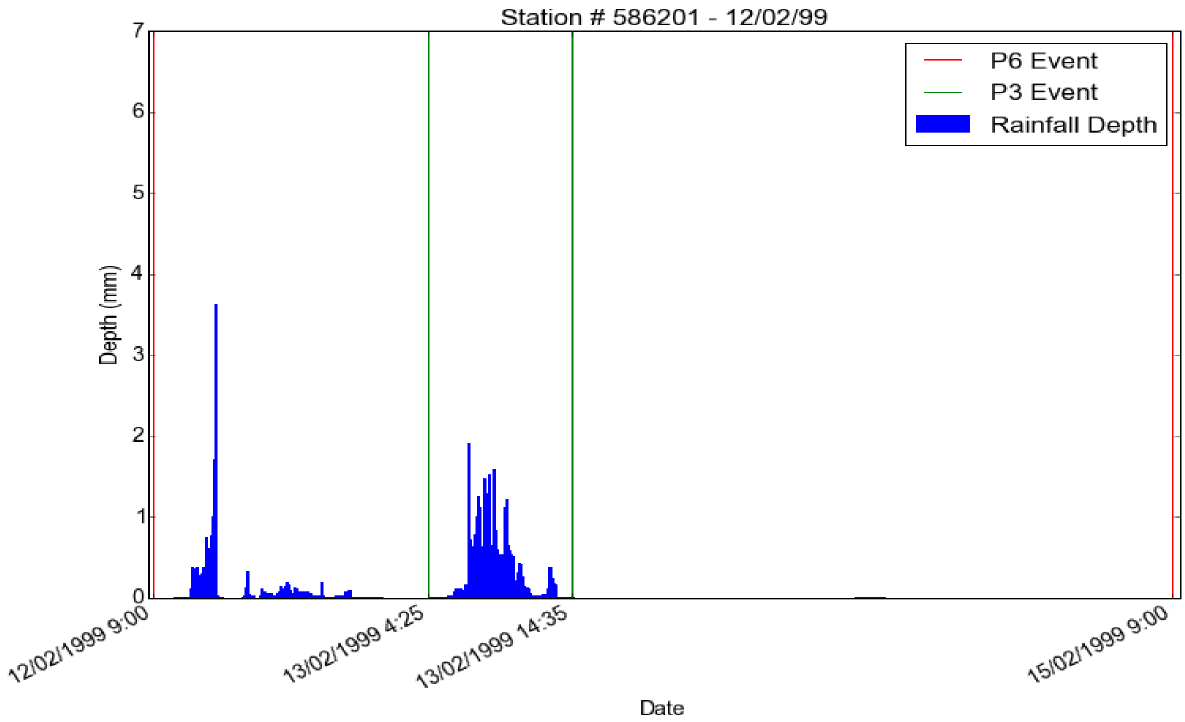


Figure 3-4 Comparison of Project 3 (initial definition) and Project 6 derived events – missing period of rainfall after the event

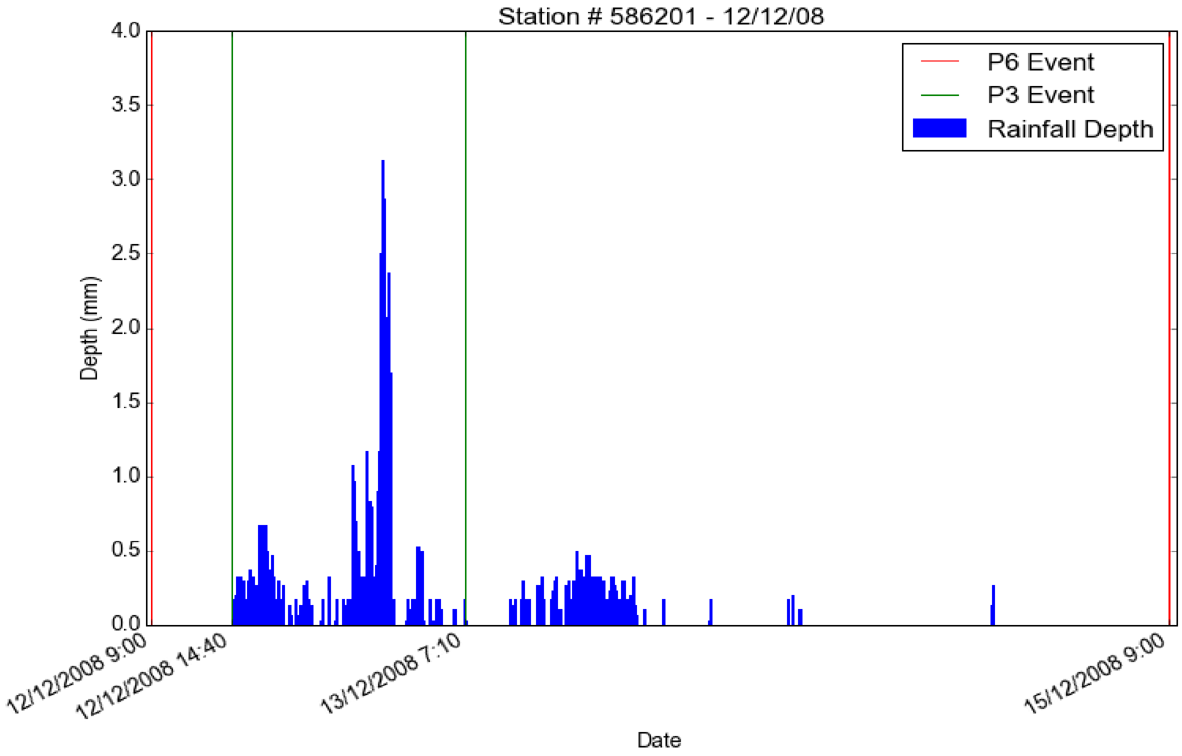
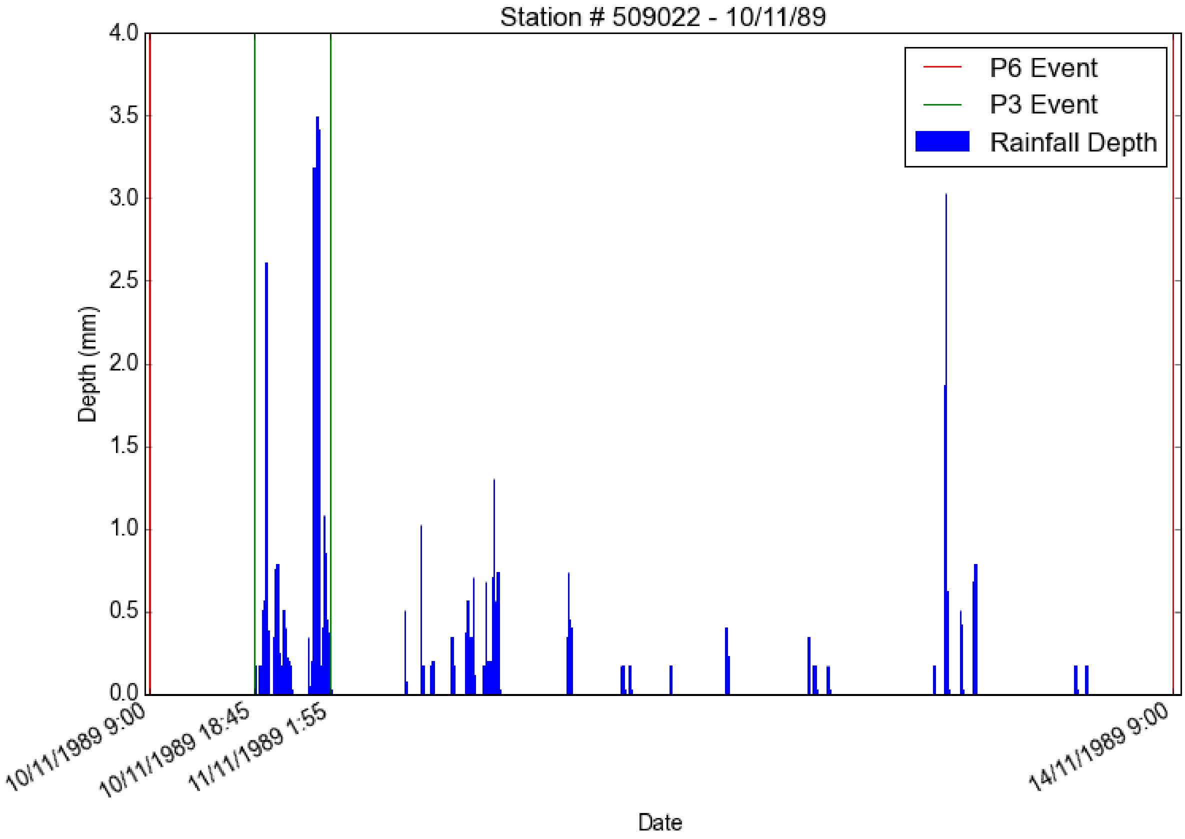


Figure 3-5 Comparison of Project 3 (initial definition) and Project 6 derived events – substantial difference in event definition



3.3.2. Final Definition

To alleviate some of the edge cases found in the initial definition a second definition was derived and compared to ARR Project 6 events. This second definition expanded on the first and used three criteria to iteratively refine the complete storm events. The first criterion is a 24 hour period with less than 10 mm of rainfall. The second criteria is a period of rainfall, equal in length to the specified duration (given a minimum of 6 hours and a maximum of 12 hours) with less than 1 to 4 mm of rainfall (dependent on the duration). The third criterion is a 1 hour period with less than 0.01 mm/h. With this criterion, the complete storm event is determined using the following steps:

- A burst rainfall period is identified as a period above the 1 EY design rainfall depth (see previous section).
- Move outwards from the end of the burst event to find the first period that meets the first criteria, both for the start and the end of the event.
- Move outwards from the point where the first criteria stopped to find the first period that meets the second criteria, both for the start and the end of the event.
- Move outwards from the point where the second criteria stopped to find the first period that meets the third criteria, both for the start and the end of the event.

The events were again plotted against comparative events from ARR Project 6 to determine whether they are consistent or not for the three catchments. Results will be presented in the following chapter.

3.4. Event Suitability

3.4.1. Critical Burst Identification

Following the identification of the burst and definition of the complete storm event, the events suitability for the given duration bin is assessed (i.e. the 6 hour duration bin). It should be noted here that the duration bin is different to the To determine if the event has a critical burst duration within the specified duration bin, event statistics are firstly calculated (including pre-burst, burst and post-burst rainfall depths, critical burst duration, etc.). The event is then either kept or discarded depending on the duration bin and critical burst duration; the critical duration is grouped based on the standard duration bins, the ranges of which can be found in Table 3-1. For example, if an event has a critical burst duration of 21.5 hours and the duration bin is 24 hours (i.e. durations ranging from 21 to 30 hours) the event will be stored for the given duration bin, whereas if the critical burst duration was 19 hours the event would be discarded and the search continues.

3.4.2. Interpolated Rainfall

Data from various sources have been included in the dataset (i.e. from the BoM and other government and external agencies), therefore the quality controlling of the data varies. While the BoM supplies quality codes to indicate the quality of each individual data point, the entire dataset still contains interpolated rainfall values (identified by a given number of repeated values). Due to the nature of these data points it is unclear whether they are erroneous or not, as some agencies supply much coarser datasets then others. For this reason, periods of interpolated rainfall have been flagged for subsequent use.

3.5. Validation against ARR Project 6 Events

As stated previously, given the events will be used for design flood analysis, the event definition needs to be consistent between ARR revision projects. Of these projects, ARR Project 6 forms one of the key design inputs that is affected by the complete storm event definition, therefore a comparison between ARR Project 6 events and those derived in this project was conducted. Key limitations of this comparison are that Project 6 derived their events manually (resulting in a more subjective fit on a case by case basis), used adjusted ARR 87 IFD curves (resulting in some minor differences in burst selection) and restrained the start and end of the event to 9:00 am. Three catchments from Project 6 were investigated, including Toomuc Creek in southern Victoria, Yates Flat Creek in south-west WA and Spring Creek in eastern QLD.

3.5.1. Start/End Criteria

By comparing the events from the two definitions it was found that the vast majority of events were very well defined. Examples of some of the well defined events can be seen in Figure 3-6 and Figure 3-7. A small percentage of the events were found to have slightly different start and end times; however, these inconsistencies were not seen to be biased in any way. Some events had a small amount of rainfall missing from the start or end of the events defined in this project (see Figure 3-8 and Figure 3-9), whilst other events can be seen to capture more rainfall at the start or end of the event; but none of these amounted to enough rainfall to noticeably affect the results. In a few cases, the additional rainfall captured or the rainfall missed was substantial enough to make a noticeable difference (see Figure 3-10); however, these are relatively unbiased so are due to the subjective case by case definition of the Project 6 events.

Figure 3-6 Comparison 1 of Project 3 and Project 6 derived events – consistent events

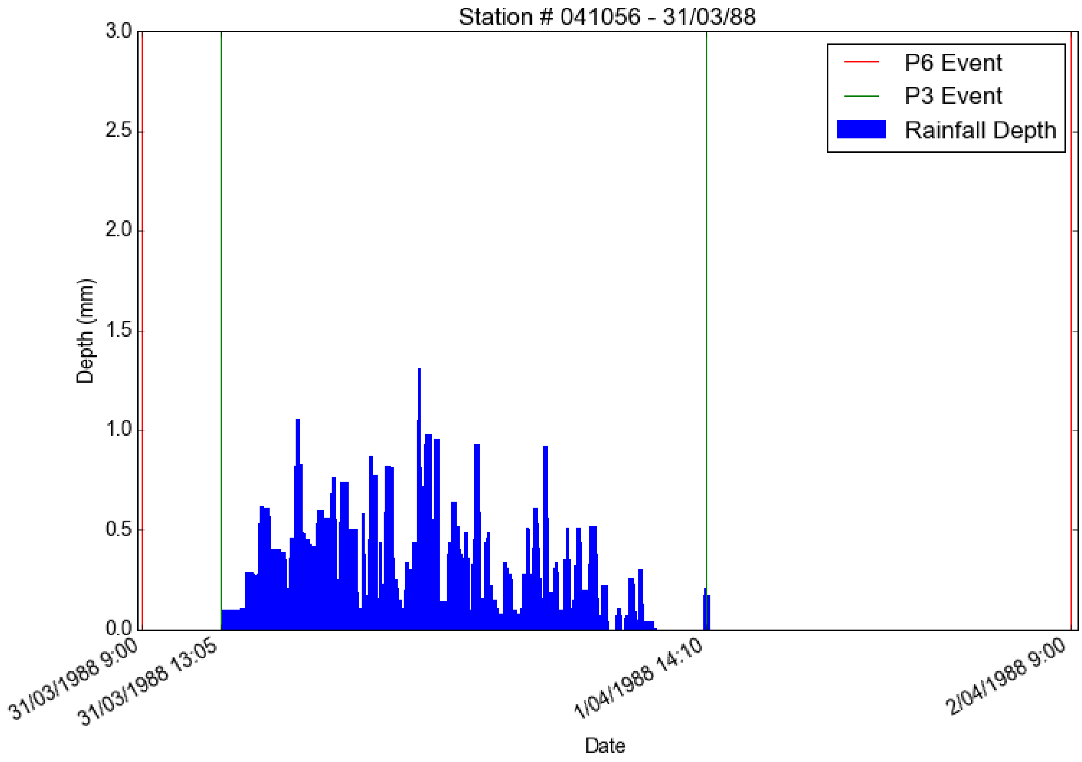


Figure 3-7 Comparison 2 of Project 3 and Project 6 derived events – consistent events

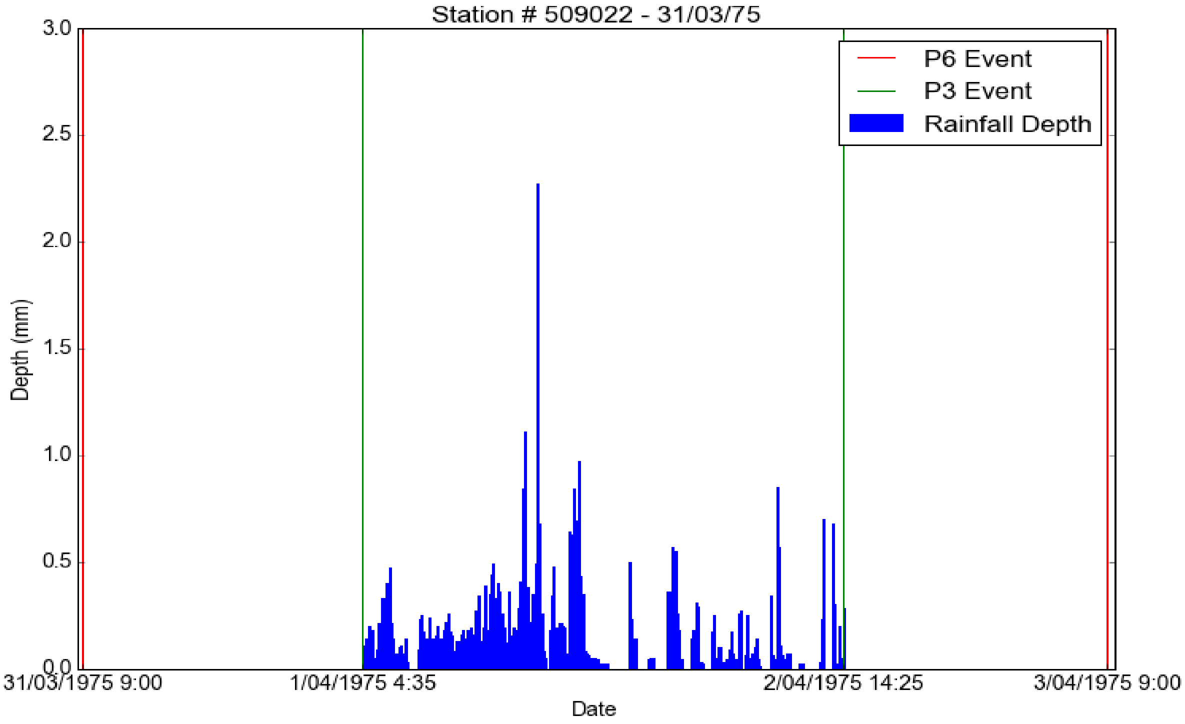


Figure 3-8 Comparison of Project 3 and Project 6 derived events – missing period of rainfall prior to the event

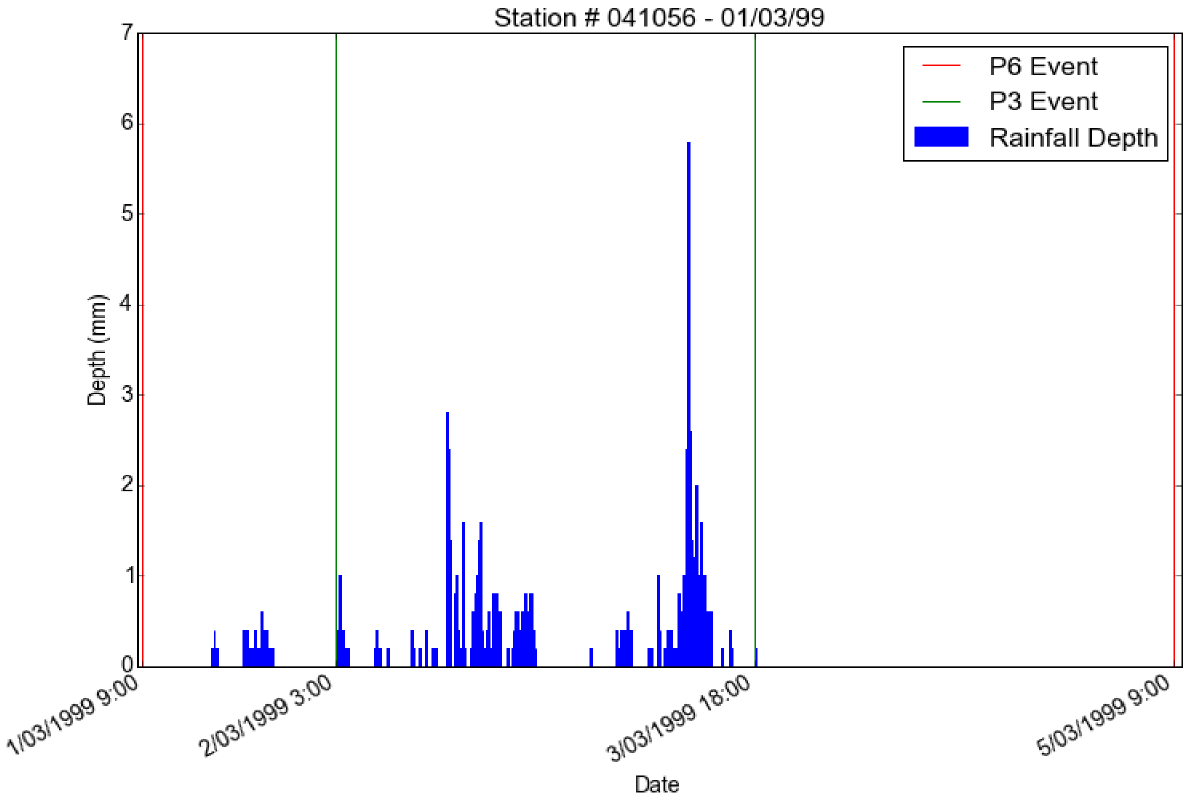


Figure 3-9 Comparison of Project 3 and Project 6 derived events – missing period of rainfall after the event

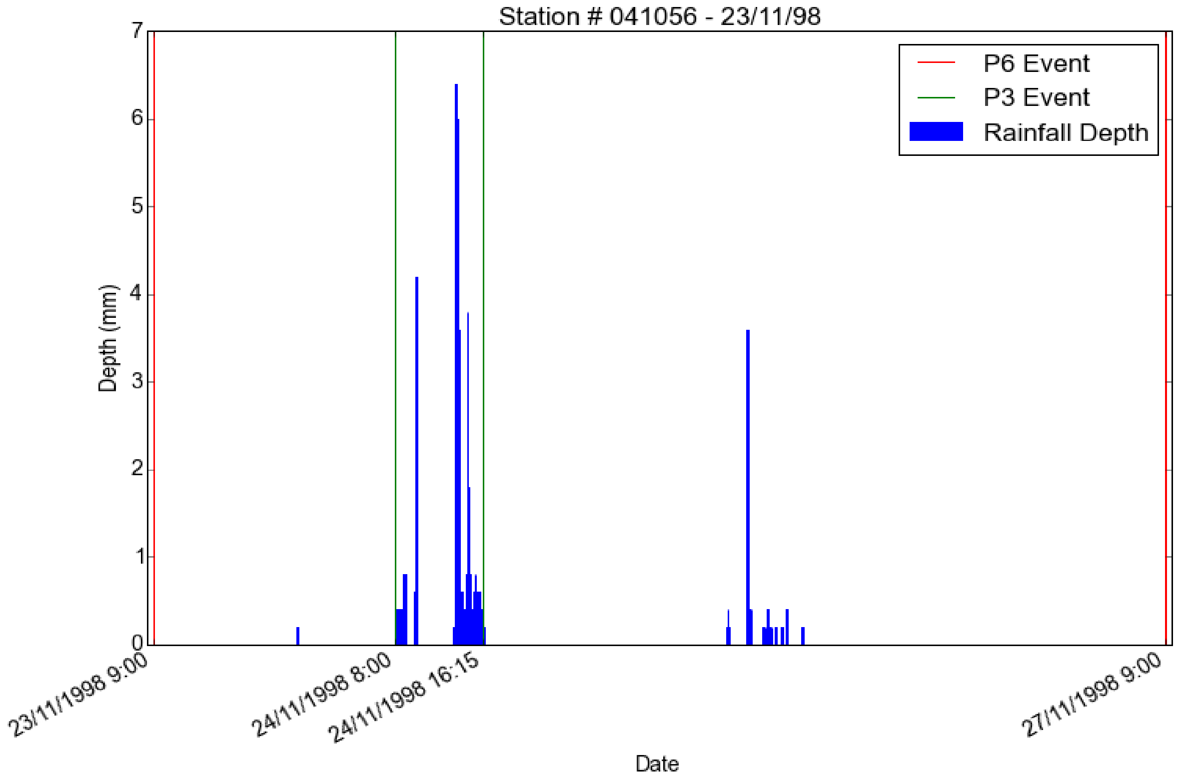
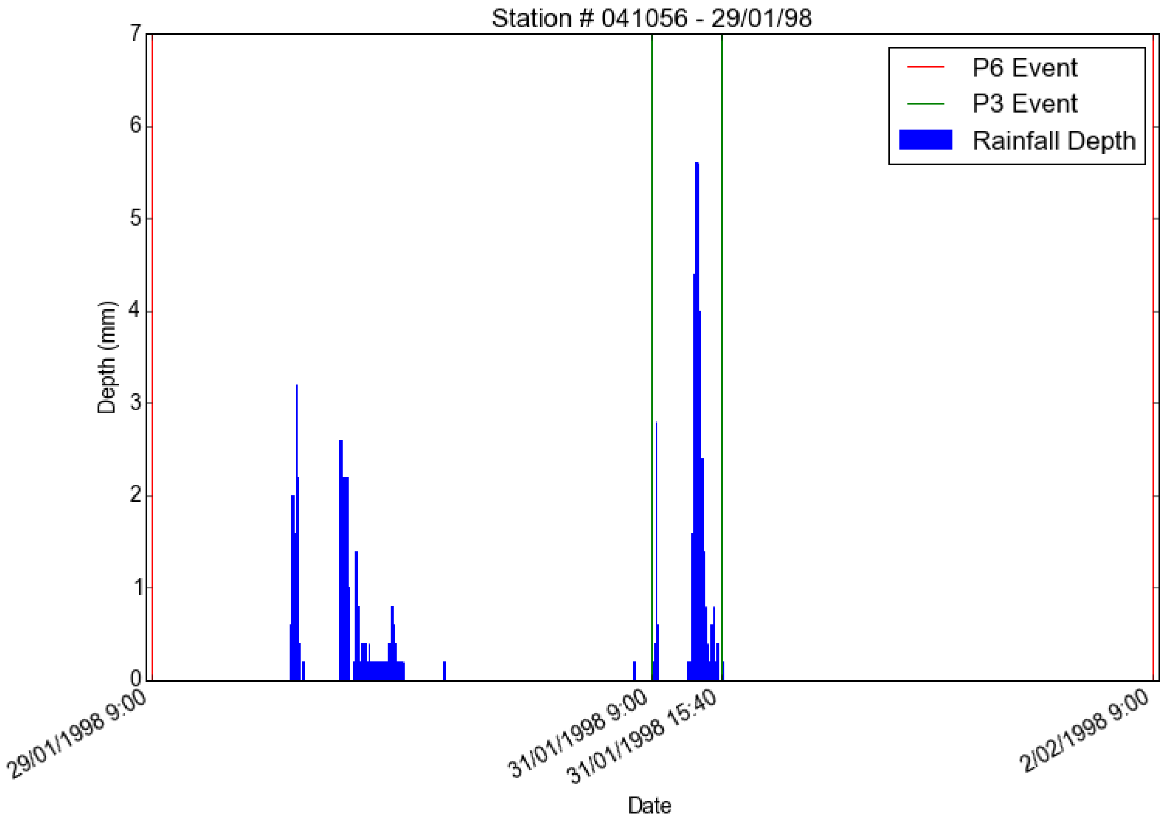


Figure 3-10 Comparison of Project 3 and Project 6 derived events – substantial difference in event definition



3.5.2. Overlapping Events

There is a small chance that the same rainfall event will be re-used for the same pluviograph station when running different duration bins. This does not result from the complete storm definition so much as the way in which rainfall bursts are identified. Rainfall bursts are identified as any rainfall period with a total rainfall depth above the 1 EY design rainfall depth for the given duration. Therefore, it is possible to have rainfall bursts that contain multiple bursts or even storm events (two rainfall bursts being most likely), with periods inbetween having little to no rainfall. Post-processing of these events should mean that it is highly unlikely that the two events would be used together. It is therefore considered that this would have negligible impact on resulting estimates.

To demonstrate further, consider a shorter duration burst above the 1 EY design rainfall depth is identified, for instance the 9 hour duration burst highlighted in blue in Figure 3-11. After defining the complete storm event, the critical burst duration is determined to be 9 hours (extremeties of which is displayed as dashed green vertical lines). This event can now be stored in the 9 hour duration bin for that station. Following this, another longer duration burst above the 1 EY design rainfall is also identified, which contains within it the previously defined burst event, for instance the 154 hour burst highlighted in blue in Figure 3-12. After defining the complete storm event for this burst, the critical burst duration is determined to be 135 hours (presented in Figure 3-12 as the green dashed lines). Because the event has a much longer critical burst duration it is also stored for this station, however this time for the 144 hour duration.

Figure 3-11 Example of two overlapping events for a single pluriograph – first event

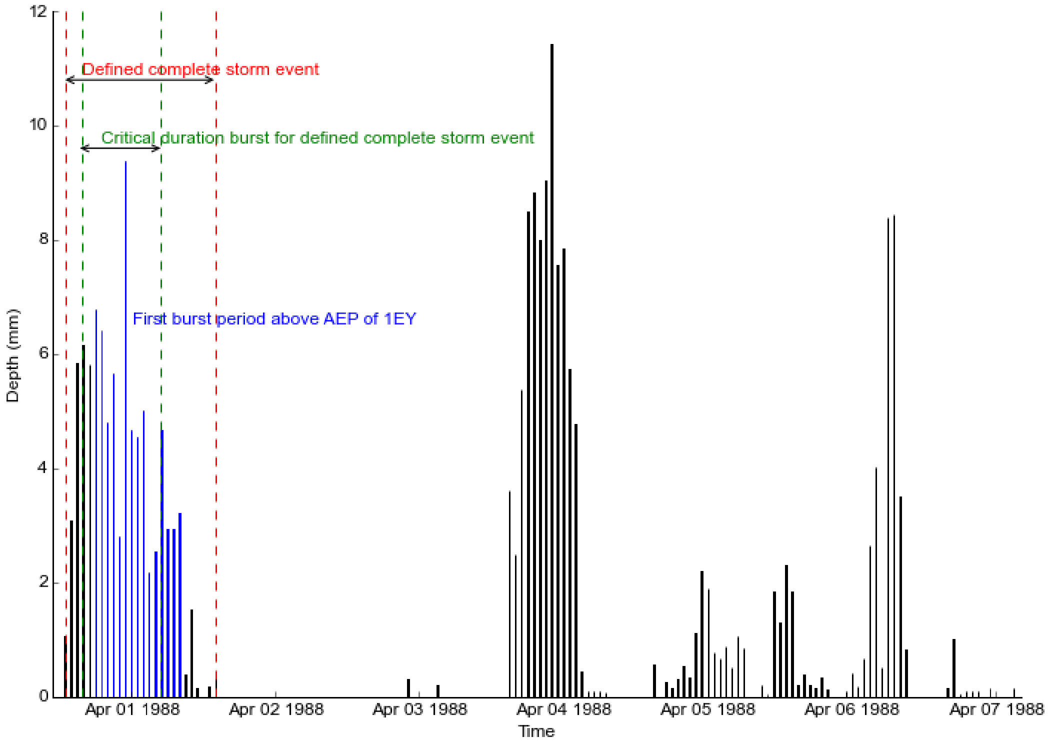
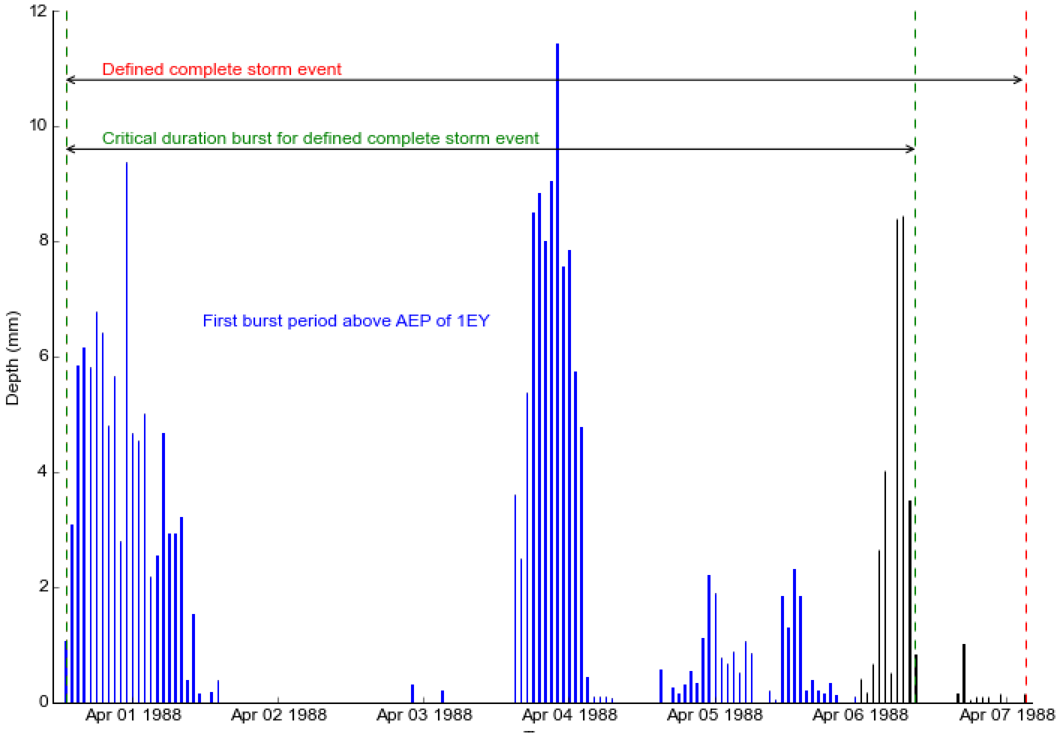


Figure 3-12 Example of two overlapping events for a single pluriograph – second event



3.5.3. Missing Events

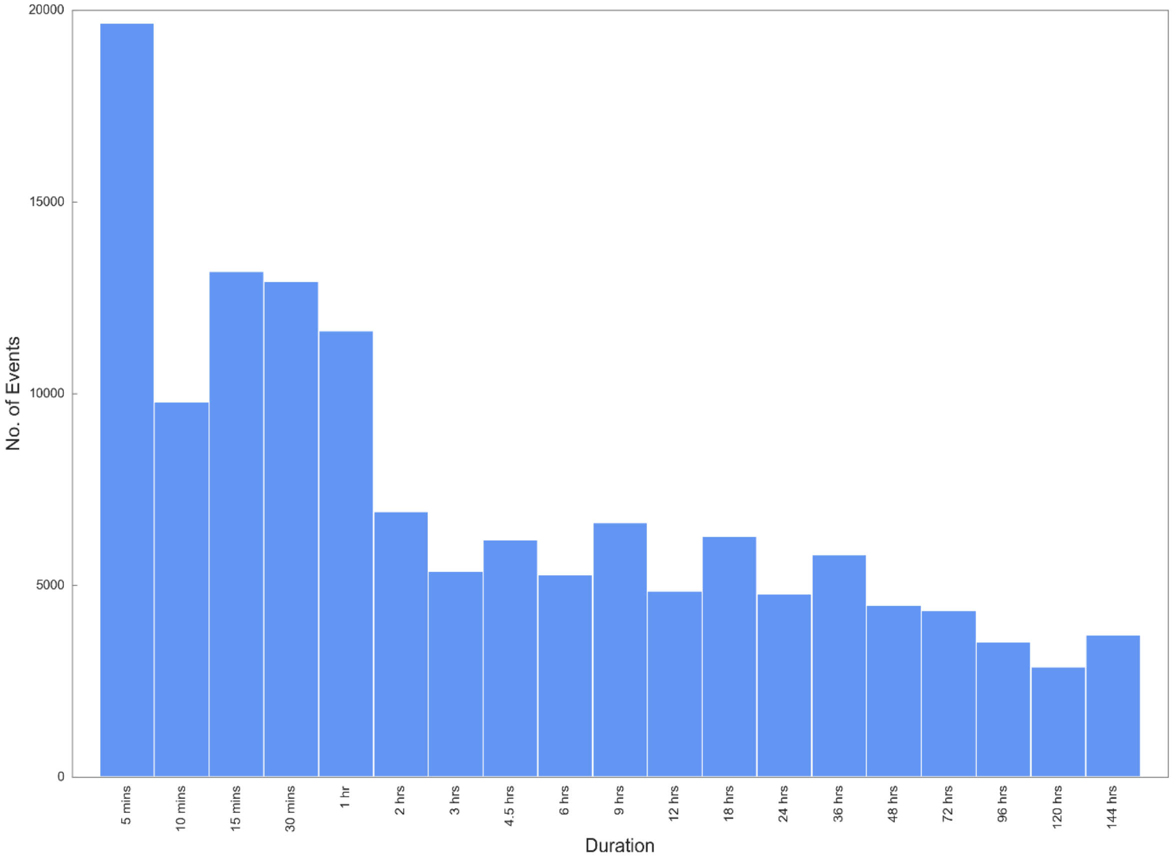
In comparing the events from this project to those from ARR Project 6, it was found that some of the events selected in ARR Project 6 were not selected in this project. Further analysis found that many of the events missed were lower than the 2013 IFD 1 EY rainfall depth. A couple were found to have a burst period above the 2013 IFD 1 EY rainfall depth; notably, these events had more frequent bursts (around the 1 EY). Further investigation found that because the bursts are selected for discrete durations, the 1 EY burst may only occur for a burst period between the standard durations. For instance, it is possible that an event with 7 to 8 hour durations above the 1 EY design rainfall depth could be excluded if the standard durations (6 or 9 hours) are below the 1 EY design rainfall threshold.

4. Sampling from the National Events Database

4.1. Overview

Having identified complete storm events for pluviographs in the BoM pluviograph database, a sampling method is required that can generate an ensemble of events for any given location throughout Australia. The number of events found in each duration bin, across Australia, can be found in Figure 4-1; events with bad quality data were not included in the count.

Figure 4-1 Number of storm events by duration bin



Generating an ensemble of design events from actual historical rainfall events will inevitably have some degree of scaling involved. Depending on the original event, scaling historical rainfall events can be problematic and has the potential to produce unrealistic rainfall patterns. At present, no consistent method is available that can guarantee a realistic pattern will be preserved after scaling.

A number of different sampling techniques can be adopted:

- *Top n from the single closest pluviograph station* – This is a simple technique, which takes the top *n* events from the closest pluviograph station (with regards to burst AEP). By selecting from the closest station, the method ensures that events are sampled from a region with similar hydro-climatic characteristics; however, the method is limited in its ability to select events based on severity, as most pluviograph stations in Australia have less than 50 years of recorded data.

- *Pool of events within a pre-defined region* (similar to ARR 1987) – Still a reasonably simple technique, this method allows for events to be sampled based on AEP, due to the substitution of temporal data with spatial data. This method is limited, however, in that events can be subject to significant scaling (i.e. when an event is taken from a location with substantially different hydro-climatic characteristics) and there can also be dramatic step changes across borders of the pre-defined regions. The method therefore relies on a well-defined region.
- *Region Of Influence (ROI) approach* – A ROI approach is the most sophisticated method described. It uses similarity criteria to determine the most representative events for a given case (based on AEP, duration and geographic location). This method is preferred above those previously described due to its ability to sample based on AEP, minimise scaling and return events from locations with similar hydro-climatic characteristics.

In order to minimise the risk of unrealistic ensembles of rainfall patterns, the technique adopted in this study was to generate an ensemble of patterns with one key principle; to minimise the amount of scaling required. As such, a ROI approach was adopted based on a number of similarity criteria.

4.2. Sampling using a ROI approach

Being that the database contains around 140,000 events, the technique initially reduces the search space by filtering the database. This is done by selecting events within 500 km of the specified coordinates and events that have a critical burst duration within the given duration bin. This removes the ability to select unrealistic events and also makes the subsequent detailed search more manageable and less computationally intensive.

Three similarity criteria are then calculated and normalised for each of the initial candidate events:

- distance similarity,
- similarity of the critical burst AEP, and
- similarity of the 2013 IFD characteristics.

Given these three characteristics, the total similarity coefficient is then calculated as the weighted average of the three separate coefficients. Every event in the pre-filtered database can then be ranked on the total similarity coefficient, and the *n* most similar events can be identified and used for further analysis.

In this section, the ranking process for the different criteria is discussed in depth, which is followed by an overview of potential issues and other considerations. This approach is similar to

ARR revision Project 4: Continuous Rainfall Sequences at a Point (Westra et al, 2012), which disaggregates daily rainfall based on daily records sampled from nearby gauges.

4.2.1. Initial Candidates

The search begins by broadly looking for candidate events; this helps to not only reduce processing times, but also to reduce the number of overlapping events from different durations. It also reduces the number of events from in the realms of the tens of thousands to thousands of candidate events, or less. This filtering process is based on three criteria:

- pluviograph must be less than 500 km from the site of interest,
- critical burst duration from the same or adjacent bin as the input duration using the standard set of durations (listed below).

The critical durations used were 5 minutes, 30 minutes, 1 hour, 2 hours, 3 hours, 4.5 hours, 6 hours, 9 hours, 12 hours, 18 hours, 24 hours, 36 hours, 48 hours, and 72 hours. For example, say we are interested in a 12 hour duration, events with critical durations from the 9, 12 and 18 hour bins will initially be selected.

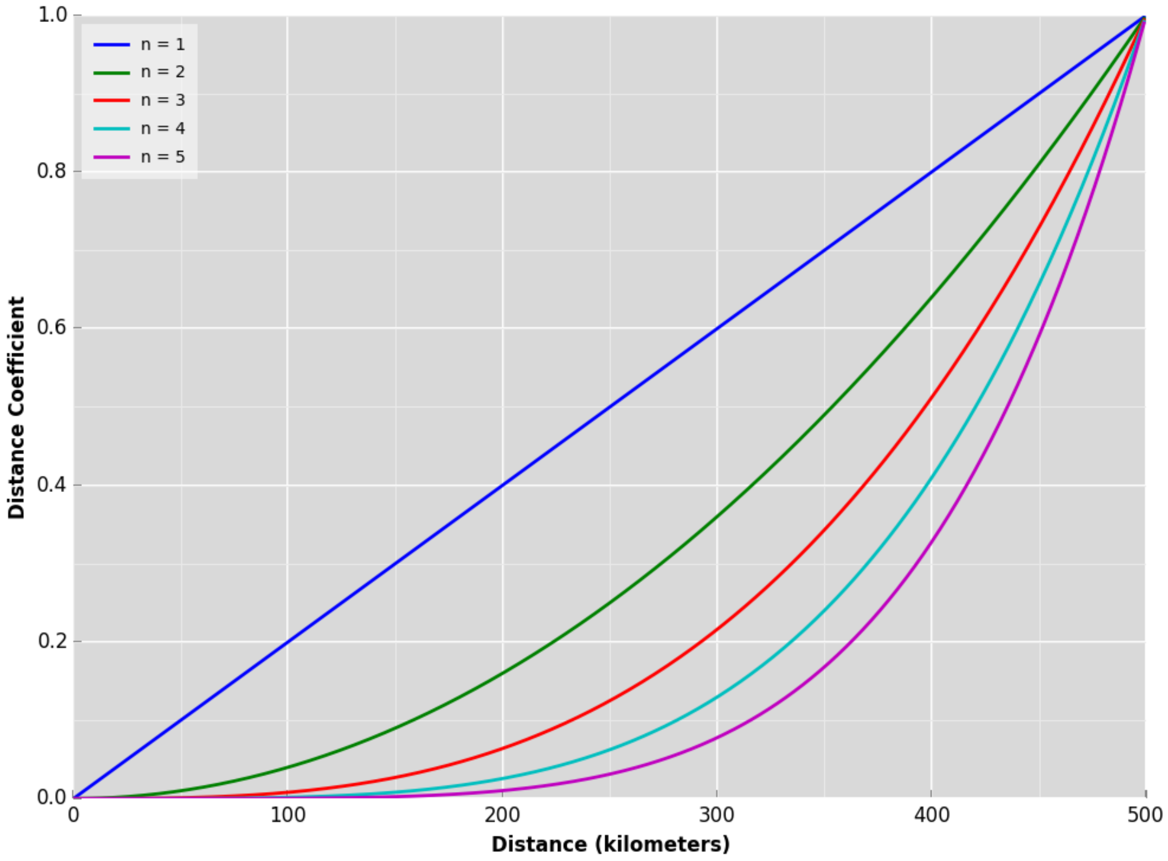
4.2.2. Distance Similarity

To calculate the distance coefficient an exponential function was adopted. This approach was adopted so that the distance coefficient will exponentially grow with distance, placing a much greater emphasis on events that are closer to the source. The distance coefficient is defined as:

$$\mathrm{c_d} = (\mathrm{d}/500)^{\mathrm{n}}$$

where $\mathrm{c_d}$ is the distance coefficient, d is the distance in kilometres and n is an exponential, chosen to be 2 in this study. This equation normalises the distance by dividing throughout by 500 km, as all initial candidate events are within a 500 km distance. The relationship between the distance and distance coefficient is demonstrated by Figure 4-2. A lower value indicates a higher degree of similarity. Alternative values for the exponential component are displayed to demonstrate the effect of changing the exponent.

Figure 4-2 Distance coefficient using different exponential values



4.2.3. AEP Similarity

The AEP coefficient represents the similarity of the specified critical burst AEP for the location of interest to the spatially shifted critical burst AEP for the candidate event. The spatially shifted AEP is determined by calculating the critical burst AEP of the candidate event as though it had occurred at the location of interest (instead of the location where the candidate event was actually recorded). The AEP coefficient is then determined by taking the absolute value of the difference between the two AEPs to create a dimensionless coefficient, as follows:

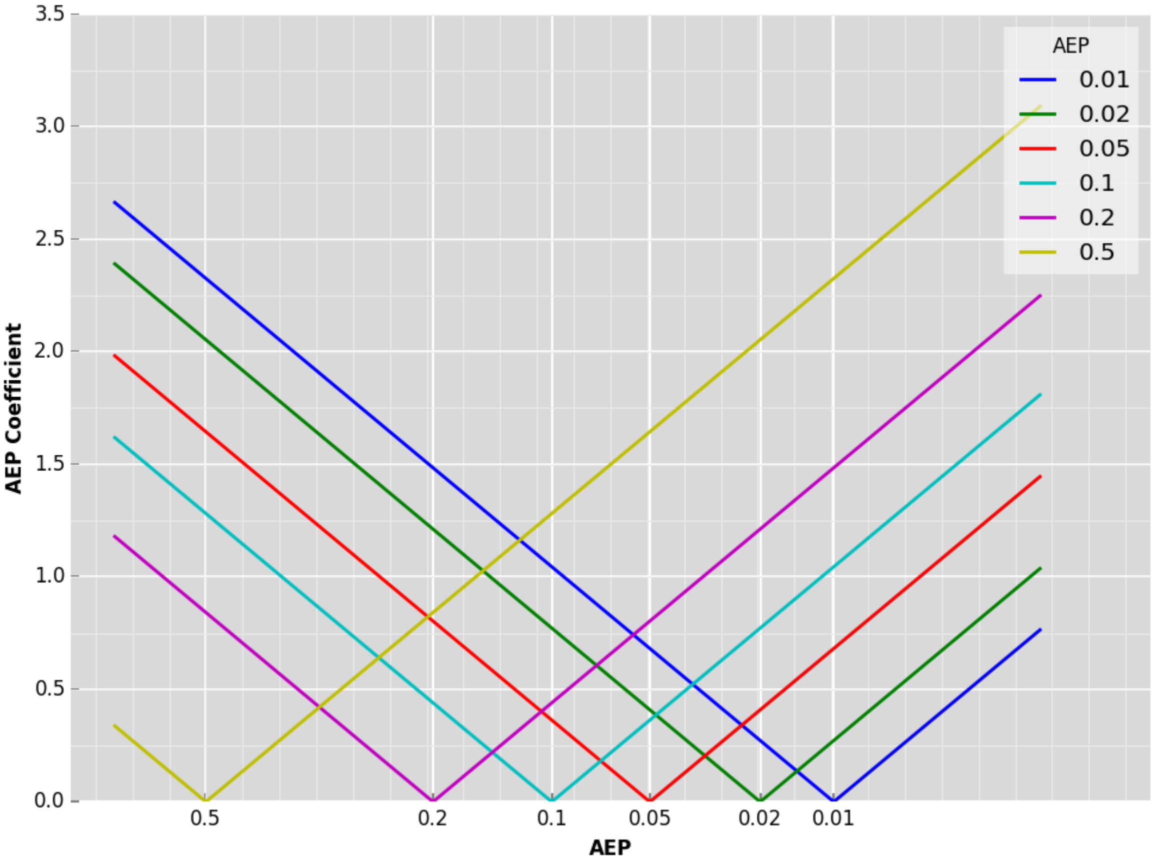
$$c_{\mathrm{aep}} = |\mathrm{NormInv}(\mathrm{AEP}_{\mathrm{local}}) - \mathrm{NormInv}(\mathrm{AEP}_{\mathrm{candidate}})|$$

where c_{aep} is the AEP coefficient, $\mathrm{NormInv}()$ is the inverse of the normal Cumulative Distribution Function (CDF), $\mathrm{AEP}_{\mathrm{local}}$ is the AEP specified for the location of interest, and $\mathrm{AEP}_{\mathrm{candidate}}$ is the spatially shifted AEP for the candidate event.

The spatially shifted AEP is used instead of the original AEP, as it provides some additional protection against the inclusion of events recorded in locations with significantly different IFD parameters. As an example, consider a search for 1% AEP event in the Sydney area. A candidate event that occurred in Orange might also be a 1% AEP event, but if it had occurred in Sydney (at the location of interest) it might only have a 10% AEP. Thus, using the spatially shifted AEP when calculating the coefficient ensures that the event is considered in the appropriate regional context.

The relationship between the two AEPs and the resulting AEP coefficient can be seen in Figure 4-3. The AEP coefficient is on the Y-axis, the spatially shifted critical burst AEP for the candidate event can be seen on the X-axis and the AEP specified for the location of interest is represented by the coloured lines, with each of the AEPs being plotted in normal probability space. For example, when looking for a 5% AEP event (i.e. represented by the red line), the same similarity is given to a candidate event with a 2 % AEP and another event with a 10 % AEP, with both resulting in an AEP coefficient of approximately 0.4.

Figure 4-3 AEP coefficient for an AEP specified at a point of interest and the spatially shifted AEP for the candidate event (x-axis)



4.2.4. IFD Similarity

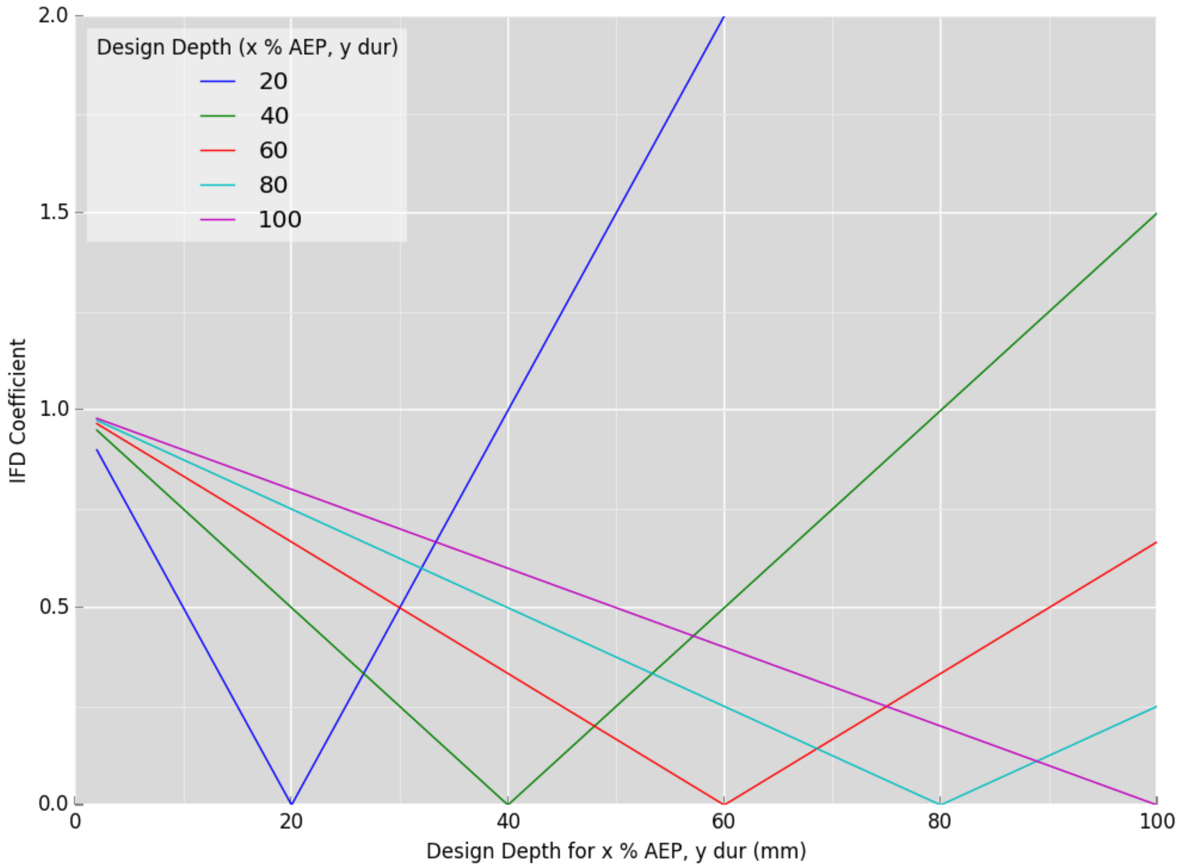
The IFD coefficient represents the similarity of storm mechanisms between the site of interest and the site where the candidate event was recorded, as represented by BoM 2013 IFD data. This is determined by calculating the percentage difference for each individual 2013 IFD table element (for a range of AEPs and durations), then calculating the average percentage difference across all 2013 IFD characteristics. The percentage difference for each IFD table element is calculated as follows:

$$c_D = \left|\frac{D_{local} - D_{candidate}}{D_{candidate}}\right|$$

Where c_D is the depth coefficient for each individual 2013 IFD table element (i.e. for a range of AEP and duration combinations), D_{local} is the design rainfall depth for a specified AEP and duration at the location of interest and $D_{candidate}$ is the design rainfall depth for the same AEP and duration at the location where the candidate event was recorded. This produces an array of coefficients for individual design depth; one for each AEP and duration combination.

The relationship between the two design depths (for the site of interest and for the location where the candidate event was recorded) and the depth coefficient is demonstrated in Figure 4-4. The depth coefficient is on the Y-axis, the design depth for the location where the candidate event is located can be seen on the X-axis and the design depth for the location of interest is represented by the coloured lines (for a number of depths). For example, if the 1% AEP 2 hour duration design depth for a given location is 40 mm (i.e. the green line), the same similarity coefficient is given to a candidate location which has a 1% AEP 2 hour duration design depth of 20 mm and another location with a 1% AEP 2 hour duration design depth of 60 mm, both resulting in a depth coefficient of 0.5.

Figure 4-4 Depth coefficient given the X % Y hour duration design depth for the location of interest (coloured lines) and for the location where the candidate event was recorded



With the array of depth coefficients calculated, the IFD coefficient is simply determined as the average of the depth coefficients for each 2013 IFD table element:

$$c_{ifd} = \overline{c_D}$$

4.2.5. Total Similarity

Finally, the total similarity coefficient can be calculated for each event in the database. This is done using a weighted average for each coefficient:

$$c_{tot} = \frac{\sum(w_n \times c_n)}{\sum w_n}$$

where c_n is the similarity coefficient (of which there are three, one for distance, IFD and AEP similarity) and w_n is the weighting for the given similarity coefficient. Given the three similarity coefficients above are adopted the total similarity is:

$$c_{tot} = \frac{(w_d \times c_d) + (w_{aep} \times c_{aep}) + (w_{ifd} \times c_{ifd})}{w_d + w_{aep} + w_{ifd}}$$

where c_d, c_{aep} and c_{ifd} are the distance, AEP and IFD similarity coefficients, respectively and the w_d, w_{aep} and w_{ifd} are the weights for the distance, AEP and IFD similarity coefficients, respectively.

4.2.6. Event Ranking

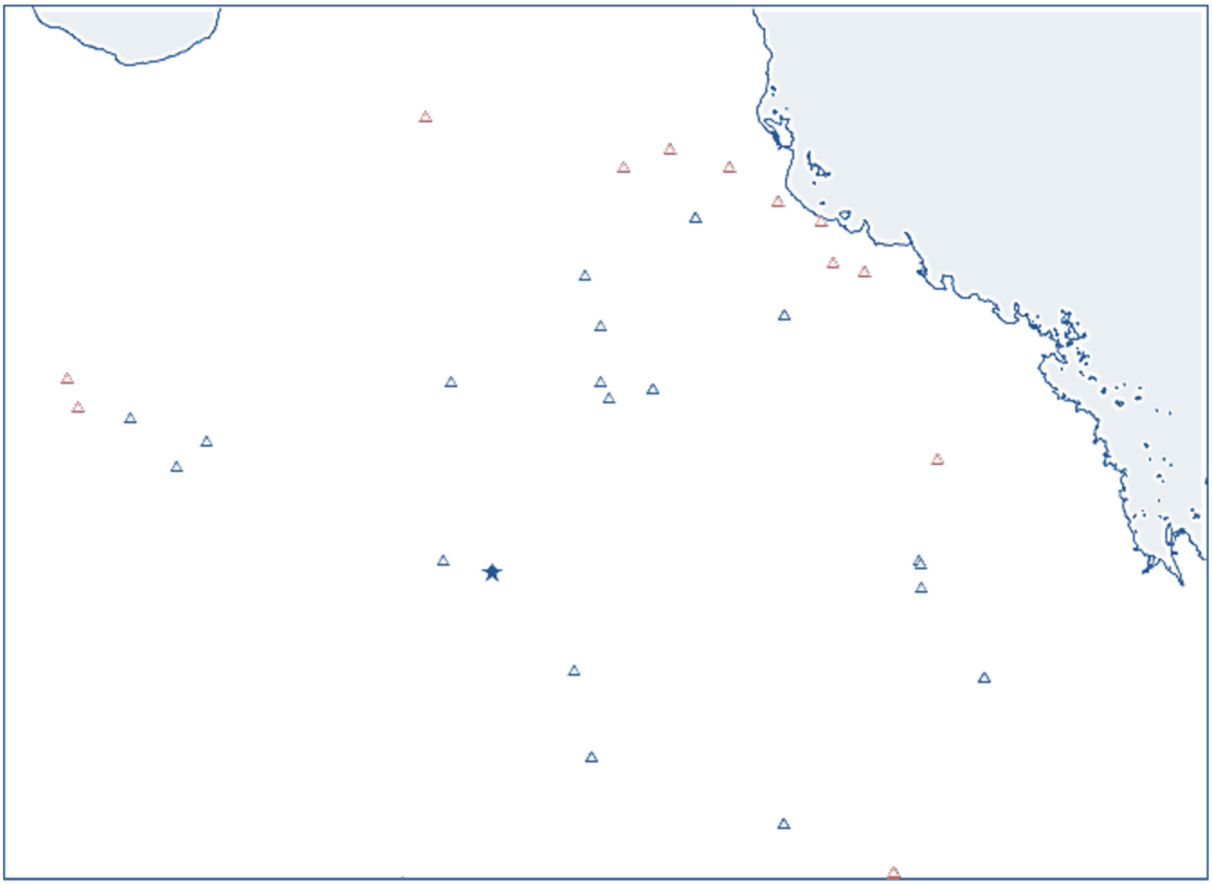
After the total similarity coefficient has been calculated for each event that fit the initial constraints, the events can be ranked based on the coefficient, in ascending order. The top *n* events are then returned for further processing, such as for a design input into a hydrologic model.

4.3. Validating Sampled Ensemble

4.3.1. Testing Similarity Criteria

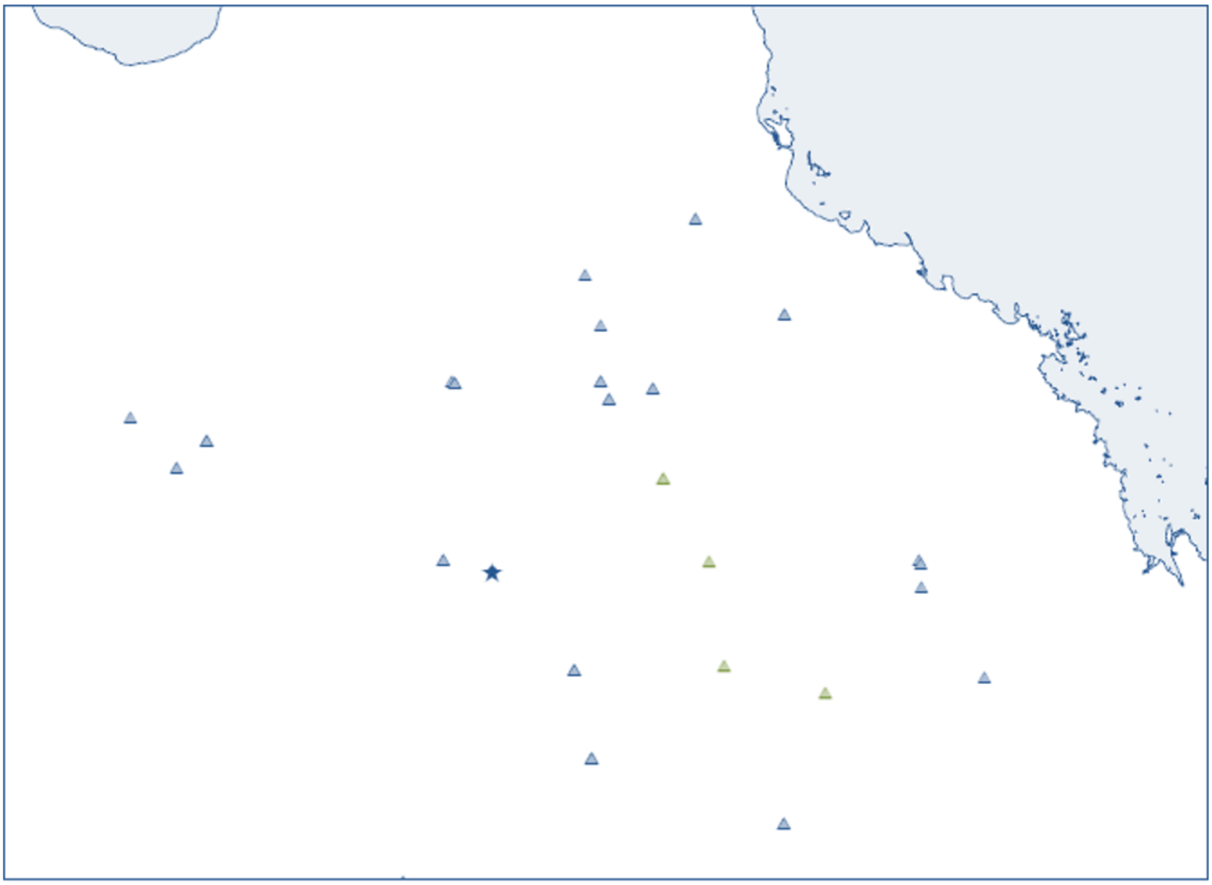
The initial analysis was performed using just the AEP and IFD similarity. Locations several hundred kilometres from the coast tended to be dominated by coastal events where pluviograph density is very high (see Figure 4-5).

Figure 4-5 Stations from which candidate events were selected using two similarity criteria (AEP and IFD similarity coefficients) along the east coast of QLD



To overcome this issue a third similarity coefficient was introduced, namely the distance coefficient. It is thought that introducing the distance coefficient would help return events which are less biased towards coastal corridors. Using the same location as before, this was tested along the east coast of Australia (see Figure 4-6). When compared to the extraction using 2 similarity coefficients, it can be seen that adding the additional coefficient results in around 9 event locations being dropped along the coastal strip (highlighted in red in Figure 4-5 and an additional 4 event locations being added closer to the point of interest (highlighted in green in Figure 4-6).

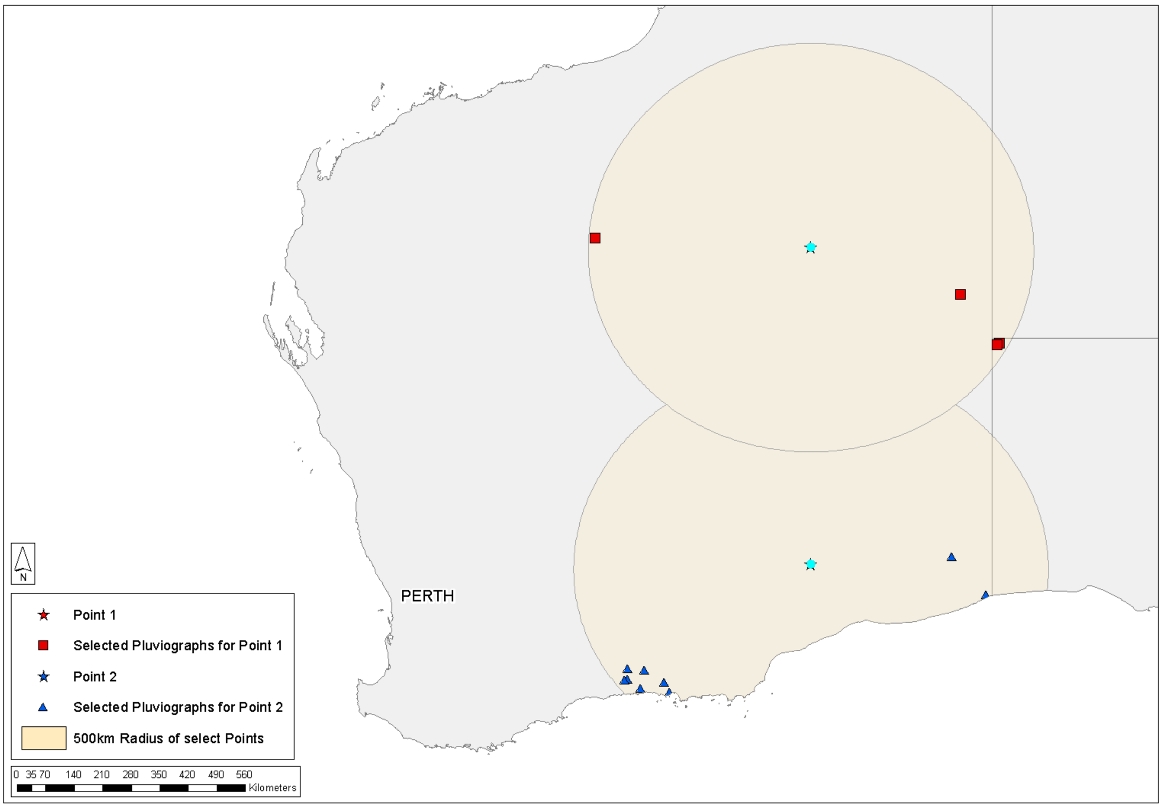
Figure 4-6 Stations from which candidate events were selected using three similarity criteria (AEP, IFD and distance similarity coefficients) along the east coast of QLD



4.3.2. Data Sparse Regions

Erratic behavior occurs when selecting the top *n* events in an area with low data density (i.e. when only a few pluviograph stations are found within a 500 km radius), such as central Australia. A large proportion of regional Western Australia, for instance, has scarce data availability with the majority of the pluviograph stations biased towards coastal regions. As an example, Figure 4-7 shows two locations in Western Australia with only a handful of stations within 500 kilometers. Point 1 only contains four stations at the extremities of the 500 km radius, with all of the top 40 events coming from these stations. These locations (and other similar locations) can be subject to sudden changes in the storm events pooled, as the addition or loss of a single pluviograph station has a substantially larger effect on the results. This issue can be reduced by increasing the search distance in data sparse regions or to divide Australia into two or more regions (i.e. arid and coastal regions), similar to ARR revision Project 5: Regional Flood Methods (Rahman et al, 2012).

Figure 4-7 Pluviograph stations from which events are selected in regional Western Australia, where pluviograph stations are sparse



4.3.3. Event Duplication

Occasionally when sampling, the same event will show up at several locations. To avoid introducing bias into the data set, only one instance of the same event should be used in the design event ensemble. An unresolved issue at this point is which instance of the event to choose. For example, if searching for 1% AEP 24 hour duration events, do we use the closest/at-site version with a 2% AEP 24 hour duration peak burst, or do we use the version from a location further away that has a 1% AEP 24 hour duration burst? As it stands, all events are ranked and assigned a coefficient that describes their similarity to the input criteria. The simplest way of dealing with this issue is simply to use the closest-matching version of the event; however, calibrating the coefficient calculations is still a problem that needs more attention.

4.3.4. Other Considerations

If the set of similar events from the nearby region is small, criteria can be enforced to ensure a “representative” sample; however, the criteria to preserve have not yet been determined. Some possible criteria to investigate are loading (front/middle/back) or time of 50% rainfall and average maximum burst duration.

If front/middle/back loading is enforced, an advantage is that events with long preceding rainfall (which tend to have a bigger impact on the peak flow than “long tail” events) get a fair representation in the resulting ensemble.

5. Conclusion

A national events database has been created that contains events throughout Australia with a rainfall burst above the 1 EY design rainfall depth. An event selection algorithm was derived that is comparable to the events derived to calibrate losses, as a part of the ARR Revision Project 6. There are some inconsistencies between the defined events; however, ARR Project 6 defined events manually which makes it difficult to replicate on a large scale across Australia.

This database can be sampled on a range of criteria including a region of influence approaches that consider distance, similarity of IFD and event AEP. These sampled events can subsequently be used in anlalysing spatial and temporal patterns in a design context. In addition, the national events database can also be used to extract events with specific characteristics for any location throughout Australia.

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Australian Rainfall & Runoff

Revision Projects

PROJECT 3: PART 2

Analysis of Pre-burst Rainfalls

STAGE 3 REPORT

ENGINEERS
AUSTRALIA
Water Engineering

Australian Rainfall & Runoff

Revision Projects

PROJECT 3: PART 3

Preliminary Testing of Temporal Pattern Ensembles

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1. Introduction

Nearly every hydrograph estimation method used for flood estimation needs a temporal pattern that describes how rainfall falls over time as a design input. Traditionally, a single temporal pattern has been used for each duration but individual patterns can have a large impact on flood estimation. While the variability of actual patterns has long been recognised in ARR 77 and Pilgrim 1969 there has been a move to considering ensembles of patterns to capture variability.

This report documents the outcomes of the preliminary testing of temporal pattern ensembles on 35 catchments across Australia. Temporal pattern ensembles were extracted and tested using a number of sampling techniques to extract a number of event types (burst, complete storm and pre-burst) from the national events database, within a design environment. A region of influence and regional sampling approach were tested.

2. Temporal Pattern Background

2.1. The Importance of Temporal Patterns

A number of inputs are required for design flood estimates; including rainfall depths, temporal and spatial patterns and rainfall losses. Temporal patterns are used in design flood estimation to describe the distribution of rainfall in time. After the rainfall depth, the temporal pattern of rainfall can have one of the biggest influence on the flood estimate. The temporal patterns are also one of the last inputs to be considered in the ARR revision projects.

Flood hydrology was historically interested in the peak flow only. Modern practice is now interested in the complete hydrograph (i.e. hydrograph shape, time of peak and volume). In order to assess these flood characteristics it is important to adopt realistic temporal patterns and account for the characteristics of complete storm events.

ARR 1987 recommended the use of the single burst Average Variability Method (AVM). One of the key aims of the AVM method is AEP neutrality therefore the AEP of the rainfall is the AEP of the resulting peak flow. Issues with this method include the domination of particular burst durations (in Zone 1 the 2hr and 9hr patterns) and rarer internal bursts. These patterns can bias flood estimates and are often unsuitable for volume-sensitive systems. Other burst approaches such as the alternating block and duration independent methods (Morris 1996, Chow et al. 1988, Keifer & Chu 1957) have many limitations. Both methods preserve probabilities across durations but do preserve many of the characteristics of real events. The alternating block does not represent a real event and the duration independent method adapts a single event. Both methods can only be considered as a way of applying a design rainfall loading that might be suitable for peak estimation but not for hydrograph estimation.

Traditionally a single temporal pattern is adopted in design. There has been a shift towards running multiple design events either by Monte Carlo simulation or ensembling. These methods consider the variability of different flood inputs.

Temporal patterns would ideally be derived from observed continuous rainfall records, rather than synthetically generated. The database used by the BoM for the Intensity Frequency Duration project was provided for this study. This meant that synthetic generation of rainfall temporal patterns is not required.

2.2. Historical Australian Approach

2.2.1. Average Variability Method

Temporal patterns for design rainfall bursts that are currently recommended in ARR 87 are based on the Average Variability Method (AVM), first proposed by Pilgrim and Cordery (1975). At present, there is a single temporal pattern for each zone and duration with 2 AEP categories. The AVM method works by finding a burst rainfall event for a given duration and zone, then ranking each period within the burst (based on the rainfall depth). The rainfall depth is then transformed into a percentage of the total burst rainfall depth. The process is repeated for many bursts, before the average rainfall percentage (across all bursts) is calculated for each ranked rainfall period (weighted towards larger events). The averaged pattern then becomes the design rainfall burst temporal pattern for that zone and duration.

Temporal Patterns in ARR 1987 were based on average variability method with 83 pluviographs with a total of 2406 station years of record The number of bursts used to derive the average pattern in each zone was equal to the number of station years, with a cap of 301 rainfall bursts per zone. Rainfall bursts were filtered, but filtering of the temporal patterns was recommended in ARR 1987 to remove rarer internal bursts, though in practice this step is often neglected.

2.2.2. Disadvantages of the AVM

The AVM method is known to result in unrealistic rainfall temporal patterns, which contain higher temporal correlations than real burst rainfall events. During development of the design temporal patterns a number of issues were encountered (which are described in Book II Section 2 2.5.2 of ARR87). Minor inconsistencies between durations and the highest intensity occurring in the first one or two time periods were overcome by the rearrangement of the sequences in the patterns. The other problem encountered was internal storm bursts being more intense than the design ARI for the overall pattern. This ultimately has an impact on the design flood estimates; this was proven by Ball (1994) who showed that the rainfall temporal pattern had a direct influence on the shape of the hydrograph and to a lesser extent, on the peak flow magnitude.

Even though filtering was applied to the design temporal patterns during their derivation, ARR87 advises that there may still be a need for further filtering at some locations. Many problems are associated with filtering temporal patterns. While small amounts of filtering is not an issue, issues arise when large amounts of filtering is applied which can significantly change the temporal pattern. While ARR87 recommends filtering, adoption varies around the country with the lack of filtering often occurring in locations where internal bursts are a major problem. In some location with significant internal burst problems filtering preserves probabilities across durations like the alternating block and duration independent method.

2.3. Alternate Approaches

Since the release of ARR 1987 there has been a myriad of temporal patterns generated for various reasons. The methods used for developing patterns include:

- completely stochastic methods, such as DRIP (Heneker, 1999),
- methods which generate patterns by sampling actual pattern information example Hoang et al (2002),
- Varga et al (2009) which is similar to DRIP but samples actual events for each disaggregation step,
- the AVM patterns developed for extreme storms (Nathan, 1999),
- sampling actual patterns either from a single pluviograph record, such as the RORB temporal pattern extractor tool (Laurenson, 2010), or
- from records within a region, such as Melbourne Water’s (Heron, 2010).

The use of actual patterns has generally been restricted to the use of bursts because they are much easier to scale, however, if they are filtered they can no longer claim to represent observed burst events.

3. Method Selection

3.1. Approaches considered for this study

There are 3 basic sampling techniques based on real events that could be adopted:

- *Top n from the single closest pluviograph station* – This is a simple technique, which takes the top *n* events from the closest pluviograph station (with regards to burst AEP). By selecting from the closest station, the method ensures that events are sampled from a region with similar hydro-climatic characteristics; however, the method is limited in its ability to select events based on severity, as most pluviograph stations in Australia have less than 50 years of recorded data.
- *Region Of Influence (ROI) approach* – A ROI approach is the most sophisticated method described. It uses similarity criteria to determine the most representative events for a given case (based on AEP, duration and geographic location). This method is conceptually preferred due to its ability to sample based on AEP, minimise scaling and return events from locations with similar hydro-climatic characteristics.
- *Pool of events within a pre-defined region* (similar to ARR 1987) – Still a reasonably simple technique, this method allows for events to be sampled based on AEP, due to the substitution of temporal data with spatial data. This method is limited, however, in that events can be subject to significant scaling (i.e. when an event is taken from a location with substantially lower rainfall characteristics) and there can also be dramatic step changes across borders of the pre-defined regions. The method therefore relies on a well-defined region.

3.2. Selected Approaches

3.2.1. Region of Influence

The ROI approach was described in Part 1 and 2 of this report and was used to determine the ratio of pre burst to burst rainfall. The same approach can also be used to extract burst or complete storms though the complete storms can only be used when scaling is minimized.

This approach is similar to ARR revision Project 4: Continuous Rainfall Sequences at a Point (Westra et al, 2012), which disaggregates daily rainfall based on daily records sampled from nearby gauges with similar rainfall characteristics

The region of influence (ROI) method uses similarity criteria to determine the most representative events. The similarity coefficient takes into consideration the AEP of the critical burst, similarity of the 2013 IFD characteristics and distance to the location of interest. Events are selected in the ROI approach from a bin of duration (eg. the 60min bin ranges from 45 to 90mins) and scaled to the AEP of interest. The ROI method aims to minimise event scaling. The sample of events chosen matches the loading characteristics in the region of interest. For this study a region of influence of 500km radius from the location of interest (catchment centroid). The method has been described in detail in Part 1 of this report (Stensmyr *et al.* 2015).

3.2.2. Region

The regional sampling method produces temporal patterns by pooling and sampling from all of the events within a defined region with similar climatic conditions. Temporal pattern regions were defined for the study based on the Natural Resource Management (NRM) regions (54 regions derived using river basins and bioregions, used for investigating the impacts of climate change, CSIRO, 2015) which were joined and drainage basin enforced to form 12 regions. Figure 1 depicts the adopted temporal pattern regions. Events were selected within the region at fixed durations. Events were binned in the following AEP ranges:

- More frequent than 7.2 years ARI (14.4% AEP) – Frequent
- 7.2 years to 37.2 years ARI (14.4% - 3.2 % AEP) – Mid
- Rarer than 37.2 years (3.2% AEP) – Rare
- Extreme (top 10 patterns)

Due to the scarcity of data across some regions (particularly for the rarer long duration bursts), events were sampled for multiple durations. This is a process where multiple bursts of different durations can be taken from the same storm event, given that the burst duration is shorter than the critical burst duration. Bursts were extracted for a total of 20 durations, with 9 durations used for the testing in this report. Table 1 summarises how many gauges and storm events exist in each region. Table 2 further breaks this down by AEP bin and duration.

This approach assumes the patterns are highly scalable. For frequent events in data rich areas the following criteria was applied but had to be relaxed for rare and long duration events:

- It is the critical burst for the storm,
- Only one event per pluviography,
- Non overlapping events,
- No embedded burst, and
- No borrowing from other similar climatic regions.

While events were selected without embedded bursts at the record location they may produce embedded bursts at the sample location.

The method has been described in detail in Part 1 of this report (Stensmyr *et al.* 2015).Where possible the events within the region are chosen to preserve the event loading of the region (refer to section 5.2). For those cases where there is not enough events available the closest events from the other bins are included, this was mainly a problem for rarer events. A check was made to ensure the selected patterns gave a reasonable spread across the regions.

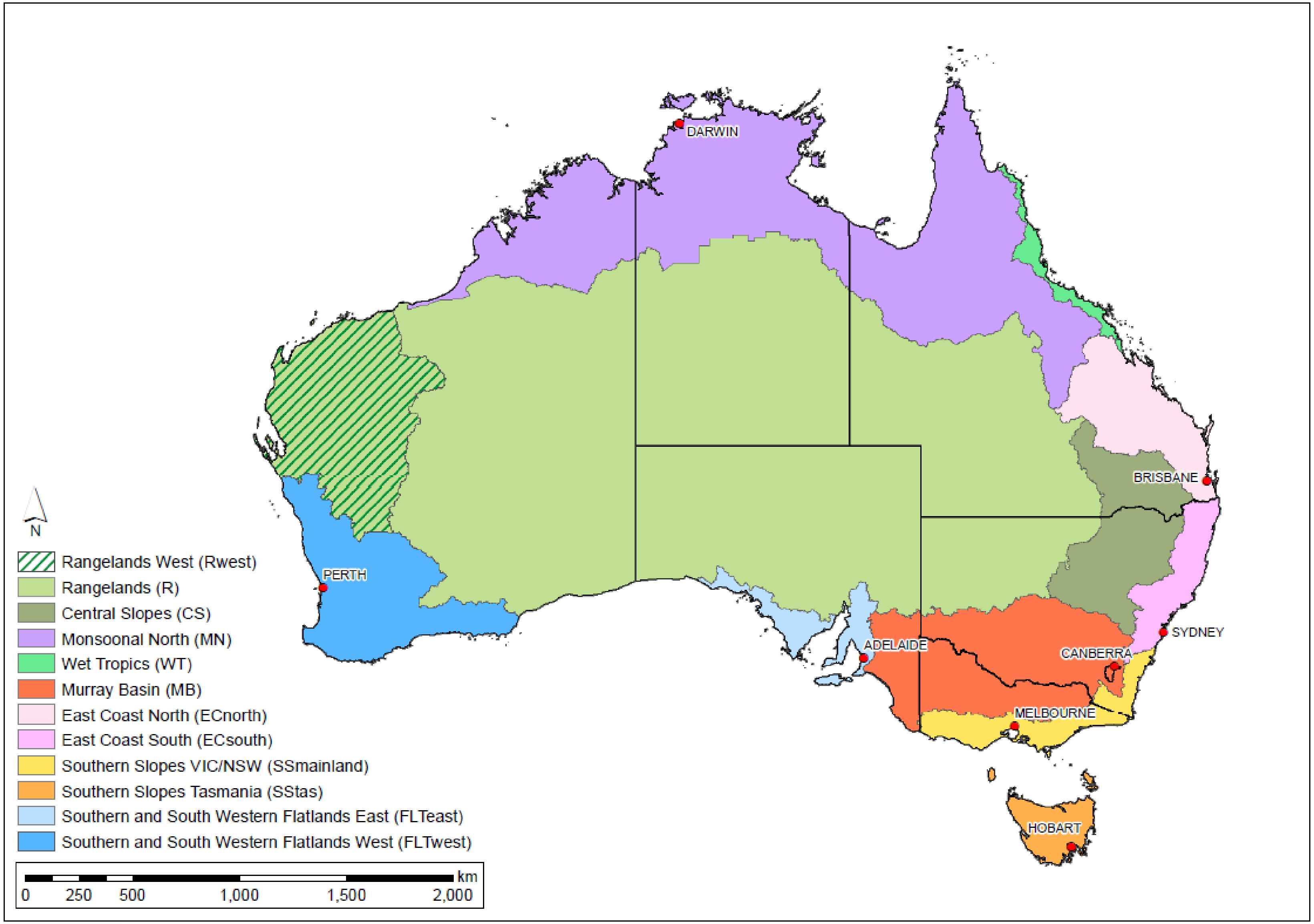

Figure 1: Temporal Patterns Regions

Table 1: Regions- Number of Gauges and Events

Region	***Number of Gauges***	***Number of Station Years***	***Number of Events***	***Average Number of Events per Station Year***
Southern Slopes (Tasmania)	110	2954	3477	1.18
Southern Slopes (mainland)	356	8536	20581	2.41
Murray Basin	233	6316	18399	2.91
Central Slopes	118	2767	7167	2.59
East Coast South	331	8067	19856	2.46
East Coast North	210	5187	12123	2.34
Wet Tropics	99	2474	5437	2.20
Monsoonal North	211	5054	12287	2.43
Rangelands West	93	2334	5391	2.31
Rangelands	226	5561	12618	2.27
Southern and South Western Flatlands (West)	349	9113	26402	2.90
Southern and South Western Flatlands (East)	56	1401	3450	2.46

Table 2: Regions – Number of events by AEP bin and duration

Duration (min)	**60**	**120**	**180**	**270**	**360**	**540**	**720**	**1080**	**1440**	**2160**	**2880**	**4320**
Duration (h)	**1**	**2**	**3**	**4.5**	**6**	**9**	**12**	**18**	**24**	**36**	**48**	**72**
Southern Slopes (Tasmaina)												
100-14.4%	159	129	146	156	136	172	100	124	81	91	66	107
14.4-3.2%	63	47	31	53	41	72	42	39	27	29	32	40
3.2-1.0%	13	9	5	5	10	10	6	4	6	2	12	1
Southern Slopes (Mainland)												
100-14.4%	886	709	687	755	611	697	584	705	471	551	402	398
14.4-3.2%	446	298	197	281	230	260	158	291	211	243	134	137
3.2-1.0%	116	70	47	40	33	37	24	50	85	41	17	12
Murray Basin												
100-14.4%	625	470	499	600	581	669	484	673	461	347	309	311
14.4-3.2%	316	219	148	194	180	201	156	270	173	134	103	86
3.2-1.0%	83	50	30	21	26	36	29	60	20	7	21	10
Central Slopes												

100-14.4%	383	213	175	196	181	209	154	212	215	226	152	141
14.4-3.2%	198	107	81	72	58	75	86	97	104	74	95	57
3.2-1.0%	34	17	14	17	8	9	10	9	25	7	5	4
East Coast (South)												
100-14.4%	1036	558	466	515	395	594	370	569	532	654	409	402
14.4-3.2%	558	298	196	197	154	256	149	211	187	258	207	86
3.2-1.0%	136	78	36	38	38	38	22	21	22	45	67	18
East Coast (North)												
100-14.4%	795	390	269	318	317	363	327	343	243	334	199	211
14.4-3.2%	392	199	122	128	100	141	113	128	95	113	65	79
3.2-1.0%	76	49	31	13	21	18	21	11	9	18	18	8
Wet Tropics												
100-14.4%	394	234	147	144	128	145	111	165	88	118	121	89
14.4-3.2%	203	111	72	82	54	58	45	71	50	44	44	44
3.2-1.0%	44	22	17	19	9	16	7	12	2	7	4	3
Monsoonal North												
100-14.4%	1007	357	184	276	217	258	192	241	274	350	261	289
14.4-3.2%	534	210	96	106	78	97	71	99	122	183	116	115
3.2-1.0%	83	47	27	19	22	20	17	11	13	21	16	7
Rangelands (West)												
100-14.4%	405	165	97	115	91	146	152	155	144	153	127	111
14.4-3.2%	216	68	45	59	51	66	62	75	37	83	46	31
3.2-1.0%	30	26	12	15	5	14	4	7	5	7	10	1
Rangelands												
100-14.4%	816	414	286	333	277	379	339	391	311	335	260	236
14.4-3.2%	431	175	108	126	103	149	122	154	114	179	107	92
3.2-1.0%	68	48	32	33	17	26	10	20	9	26	21	14
Southern and South Western Flatlands (West)												
100-14.4%	956	839	752	915	792	1007	764	805	521	824	827	988
14.4-3.2%	522	309	254	318	304	367	238	349	194	256	284	254
3.2-1.0%	124	77	46	53	26	51	20	32	16	106	29	20
Southern and South Western Flatlands (East)												
100-14.4%	151	161	164	147	123	165	88	110	80	147	85	77
14.4-3.2%	65	48	30	45	29	55	25	35	36	45	23	23
3.2-1.0%	17	7	4	4	1	9	1	2	9	3	0	1

3.2.3. Event Types

Traditionally, a peak burst approach has been adopted in Australian practice. For a burst event the critical burst of the storm event is modelled only (Figure 2). Burst initial losses are applied. The approach has several drawbacks, most significantly its disregard for the pre-burst rainfall. Three event types were considered in this study:

- Burst
- Burst plus pre-burst, and
- Complete storm - for ROI only

In the Burst plus pre-burst approach, an approximate to a complete event, the pre-burst depth is predicted so that storm losses can be used. In a complete storm approach the complete storm event is modelled (Figure 2). The region approach is not applied for complete storms as this would require assuming the pre-burst is scalable over a wide range. Table 3 summarises the event types and methods adopted for this study.

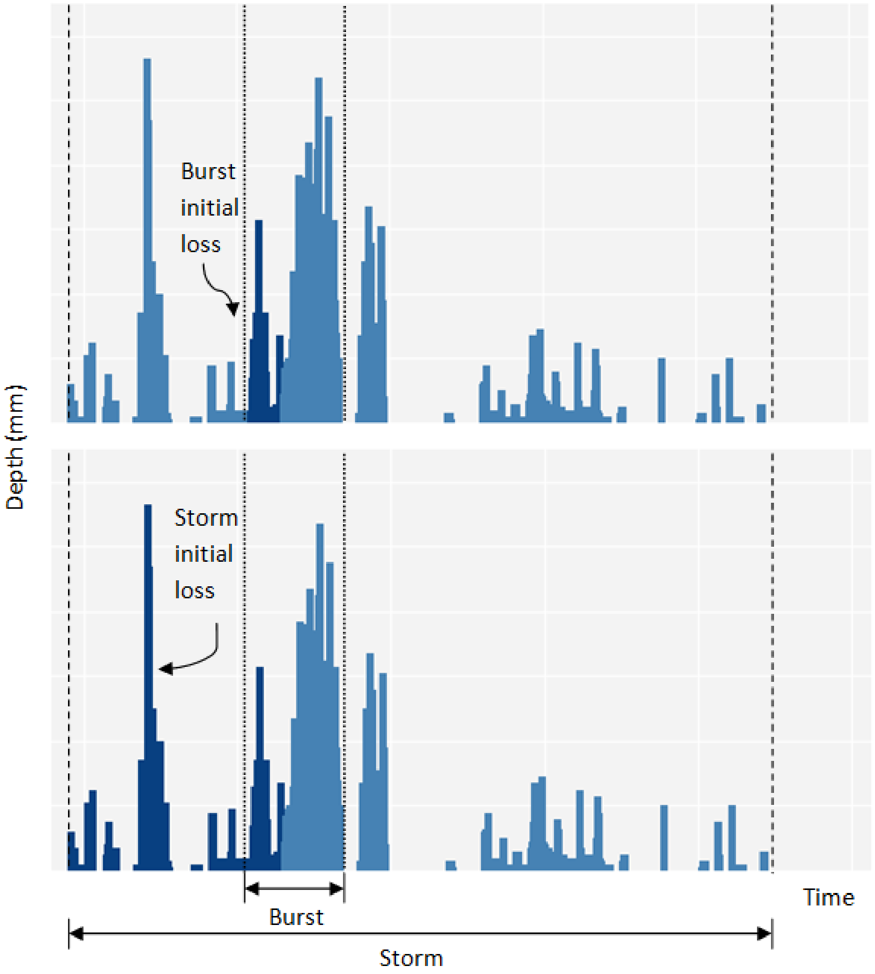

Figure 2: Event Types

Table 3: Event Types and Methods

Method	Event Type		
	Burst	Burst Plus Pre Burst	Complete Storm
ROI	🟦	🟦	🟦
Region	🟦	🟦	

4. Available Data

4.1. Events Database

An event database consisting of storm events extracted from the BoM quality controlled database pluviograph data (developed as part of ARR Revision Project 1) was used in the study. The events database consists of around 102,452 events from about 2,290 pluviograph stations across Australia. More detail can be found in Part 1 of the Project 3 report (Stensmyr *et al.* 2015). Events with interpolated data were not used.

4.2. Pre Burst Rainfall

The pre-burst rainfall is the portion of rainfall that occurs before the start of the critical burst of the storm event (Figure 3). Pre-burst rainfall depths were calculated for each event in the events database.

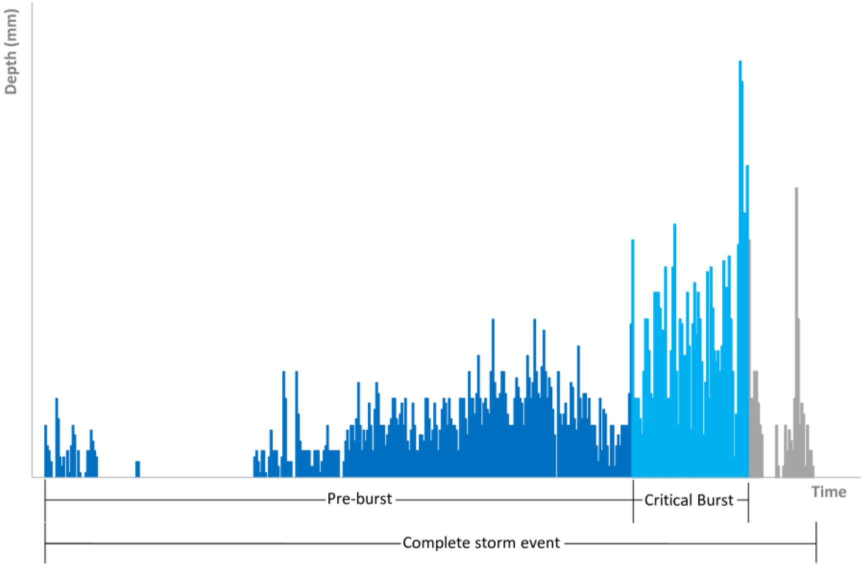

Figure 3: Storm Event Definition

The pre-burst to burst ratio is calculated as the proportion the pre-burst rainfall depth of the critical burst rainfall depth. Mapping of some pre-burst characteristics was carried out using a regular grid across Australia. Detailed discussion on the estimation and extraction of pre-burst rainfall is the subject of Part 2 of this report (Loveridge et al. 2015).

4.3. Test Catchments

A total of 35 catchments were selected for testing of the temporal patterns methods (Figure 4) which were used by ARR Project 6 – Losses for Design Flood Estimation. The Project 6 catchments were chosen to provide consistency across ARR projects, similar data requirements to the current study and the availability of calibrated hydrologic (RORB) models. A flood frequency analysis had also previously been undertaken for some of the catchments and was available for use in the study. For those catchments where flood frequency analysis was not previously undertaken, it was undertaken using FLIKE.

These consist of:

- 10 catchments from Phase 1, and
- 25 of the 28 catchments from Phase 4.

The catchments used for Project 6 met the following data requirements:

- 20 years of overlapping streamflow and pluviograph data, and
- An area less than 60 km^2 - to avoid significant routing effects.

Three catchments from the Project 6 work were not included in the analysis for the following reasons:

- Myponga River - difficulty in calibrating this catchment, the stream is not well defined at the gauging location. There are a number of natural depressions near the site and the area is very flat.
- Tarago River - Tarago River was recalibrated in a later study and was found to have very high losses when calibrated to the FFA. As this calibration was not done in the Project 6 work using the new losses would be inconsistent with the other catchments.
- Kanjenjie Creek Tributary - issues with the recorded flows. The loss values were inconsistent with other catchments.

More details on the selection of the catchments can be found in (Hill et al. 2014). The catchments are reasonable geographic distribution across Australia (Figure 4). Table 4 summarises the catchment characteristics.

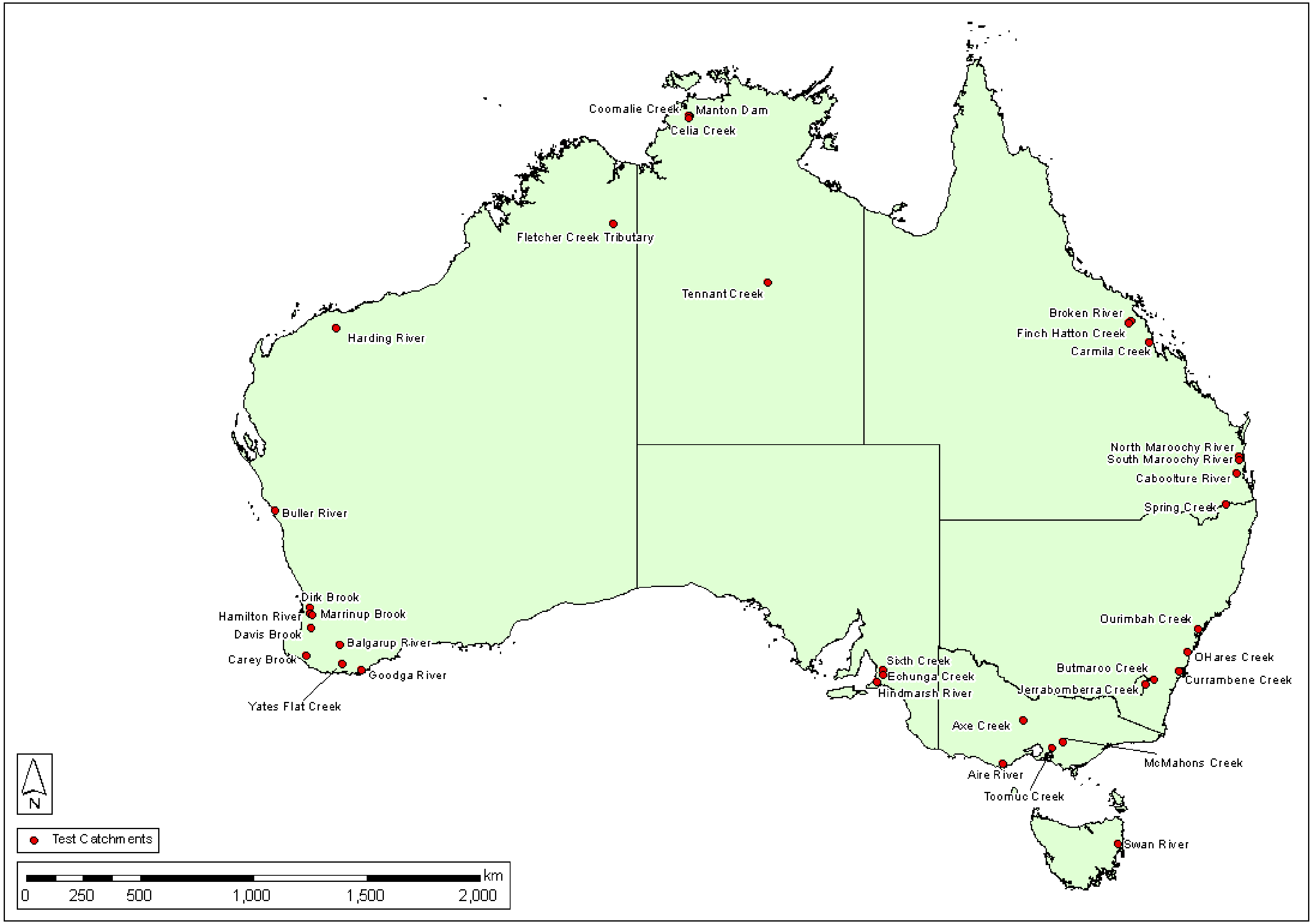

Figure 4: Test Catchments Locations

Table 4: Test Catchments

Gauge No.	Station Name	State	Region	Area (km^2)	Record Length (yrs)	Latitude (centroid)	Longitude (centroid)
2219	Swan River u/s Hardings Falls	TAS	Southern Slopes (Tasmania)	38	29	-41.8186	148.1042
235219	Aire River - Wyelangta	VIC	Southern Slopes (mainland)	90	36	-38.6627	143.5444
216004	Currambene Creek - Falls Creek	NSW	Southern Slopes (mainland)	95	41	-34.9927	150.5354
229106	McMahons Creek - u/s Weir	VIC	Southern Slopes (mainland)	40	31	-37.7625	145.9089
228217	Toomuc Creek - Pakenham	VIC	Southern Slopes (mainland)	42	34	-37.9991	145.4673
406216A	Axe Creek - Sedgewick	VIC	Murray Basin	34	36	-36.9413	144.3278
411003	Butmaroo Creek - Butmaroo	NSW	Murray Basin	65	33	-35.3212	149.5428
410743	Jerrabomberra Creek - Four Mile Creek	NSW	Murray Basin	52	30	-35.4852	149.1886
422321	Spring Creek - Killarney	QLD	Central Slopes	32	39	-28.3397	152.3778
213200	O'Hares Creek - Wedderburn	NSW	East Coast South	73	34	-34.2143	150.8662
211013	Ourimbah Creek - u/s Weir	NSW	East Coast South	83	35	-33.2976	151.2797
142001A	Caboolture River - Upper Caboolture	QLD	East Coast North	94	46	-27.1083	152.8219
141009	North Maroochy River - Eumundi	QLD	East Coast North	41	30	-26.4698	152.9223
141001B	South Maroochy River - Kiamba	QLD	East Coast North	33	26	-26.6157	152.8857
126003A	Carmila Creek - Carmila	QLD	Wet Tropics	82	38	-21.9288	149.3413
125006A	Finch Hatton Creek - Dam Site	QLD	Wet Tropics	36	36	-21.0702	148.6326
120216A	Broken River - Old Racecourse	QLD	Monsoonal North	78	42	-21.1876	148.5093
G8150151	Celia Creek - u/s Darwin R Dam	NT	Monsoonal North	52	38	-12.9418	131.0570
G8170066	Coomalie Creek - Stuart HWY	NT	Monsoonal North	82	51	-13.0241	131.0802

809312	Fletcher Creek Trib. - Frog Hollow	WA	Monsoonal North	31	44	-17.2488	128.0498
G817007	Manton River u/s Manton Dam	NT	Monsoonal North	29	47	-12.9247	131.1217
709007	Harding River - Marmurrina Pool U-South	WA	Rangelands West	49	24	-21.3443	117.0788
G0290240	Tennant Creek - Old Telegraph Stn	NT	Rangelands	72	39	-19.5734	134.1852
609005	Balgarup River - Mandelup Pool	WA	Southern and South Western Flatlands (West)	82	36	-33.9453	117.2008
701006	Buller River - Buller	WA	Southern and South Western Flatlands (West)	34	26	-28.6208	114.6467
608002	Carey Brook - Staircase Rd	WA	Southern and South Western Flatlands (West)	30	36	-34.3627	115.8929
614047	Davis Brook - Murray Valley Plntn	WA	Southern and South Western Flatlands (West)	66	46	-33.2784	116.0587
614005	Dirk Brook - Kentish Farm	WA	Southern and South Western Flatlands (West)	36	31	-32.4438	116.0452
602199	Goodga River - Black Cat	WA	Southern and South Western Flatlands (West)	49	46	-34.9145	118.0745
612004	Hamilton River - Worsley	WA	Southern and South Western Flatlands (West)	32	40	-32.6954	116.0148
614001B	Marrinup Brook - Brookdale Siding	WA	Southern and South Western Flatlands (West)	46	40	-32.7292	116.1243
603190	Yates Flat Creek - Woonanup	WA	Southern and South Western Flatlands (West)	53	48	-34.6956	117.3334
AW503506	Echunga Creek u/s Mt. Bold Res.	SA	Southern and South Western Flatlands (East)	34	37	-35.1089	138.7714
AW501500	Hindmarsh River - Hindmarsh Vy Res Offtake	SA	Southern and South Western Flatlands (East)	56	43	-35.4253	138.5593
AW50452	Sixth Creek - Castambul	SA	Southern and South Western Flatlands (East)	44	33	-34.9200	138.7698

4.3.1. Parameters

Table 5 summarises the key model parameters used for each catchment including: initial loss, continuing loss, k_c and baseflow. These parameters were available from ARR Project 6 (Hill et al. 2014). Continuing loss values from ARR Project 6 were available for a 60 minute timestep. The continuing loss was needed to a finer time step as a 60 minute time step does not adequately represent the rising limb of the shorter duration events. 15 and 5 minute equivalent continuing loss values were calculated. For consistency all events were run at 5 minutes . Baseflow is a minor component of the flow for most catchments other than Hamilton River and Carey Brook.

Table 5: Test Catchment Parameters

Gauge No.	Station Name	Storm IL (mm)	Burst IL (mm)	CL_{60min}	CL_{5min}	k_c	Baseflow (%)
2219	Swan River u/s Hardings Falls	40.0	12.0	0.50	0.67	10.0	0.5
235219	Aire River - Wyelangta	17.0	11.4	3.10	3.72	17.0	2.6
216004	Currambene Creek - Falls Creek	35.0	23.8	3.90	5.07	11.0	1.1
229106	McMahons Creek - u/s Weir	20.0	14.6	3.70	4.81	20.0	0.2
228217	Toomuc Creek - Pakenham	24.0	11.0	2.50	2.86	12.0	0.6
406216A	Axe Creek - Sedgewick	28.0	25.0	6.00	10.20	8.5	1.3
411003	Butmaroo Creek - Butmaroo	40.0	35.0	2.60	3.64	7.0	0.1
410743	Jerrabomberra Creek - Four Mile Creek	22.0	8.0	2.10	4.57	4.0	0.4
422321	Spring Creek - Killarney	30.0	15.0	5.10	9.18	6.0	3.4
213200	O'Hares Creek - Wedderburn	60.0	45.3	1.60	2.88	9.0	4.2
211013	Ourimbah Creek - u/s Weir	40.0	35.5	3.70	4.81	22.0	1.8
142001A	Caboolture River - Upper Caboolture	50.0	26.0	1.40	2.66	11.0	0.1
141009	North Maroochy River - Eumundi	20.0	7.0	2.20	3.19	20.0	1.5
141001B	South Maroochy River - Kiamba	38.0	14.1	2.70	4.32	10.0	0.1
126003A	Carmila Creek - Carmila	70.0	11.0	3.10	4.96	9.5	1.4
125006A	Finch Hatton Creek - Dam Site	23.0	15.0	5.20	8.62	4.0	0.9
120216A	Broken River - Old Racecourse	68.0	35.5	6.20	9.92	11.0	0.2
G8150151	Celia Creek - u/s Darwin R Dam	25.0	20.0	5.40	7.56	14.0	2.3
G8170066	Coomalie Creek - Stuart HWY	50.0	40.0	8.10	11.34	18.0	1.5

809312	Fletcher Creek Trib. - Frog Hollow	30.0	21.7	10.40	20.80	2.5	0.0
G817007	Manton River u/s Manton Dam	42.0	11.0	1.60	2.53	8.0	0.8
709007	Harding River - Marmurrina Pool U-South	60.0	50.1	9.30	15.81	5.0	0.0
G0290240	Tennant Creek - Old Telegraph Stn	0.0	0.0	5.20	6.76	8.9	0.0
609005	Balgarup River - Mandelup Pool	25.0	20.5	2.50	3.50	9.6	0.2
701006	Buller River - Buller	32.0	30.5	3.80	6.65	3.2	0.2
608002	Carey Brook - Staircase Rd	20.0	18.9	3.80	6.84	25.0	71.5
614047	Davis Brook - Murray Valley Plntn	25.0	22.0	8.10	15.39	18.5	9.6
614005	Dirk Brook - Kentish Farm	14.0	6.0	6.70	9.44	14.0	5.9
602199	Goodga River - Black Cat	30.0	27.2	4.80	9.12	16.0	2.2
612004	Hamilton River - Worsley	47.0	42.4	3.30	5.28	19.0	14.4
614001B	Marrinup Brook - Brookdale Siding	16.0	15.7	7.30	13.87	17.5	3.0
603190	Yates Flat Creek - Woonanup	27.0	15.0	0.80	2.00	10.0	1.2
AW503506	Echunga Creek u/s Mt. Bold Res.	25.0	24.4	2.20	3.52	6.9	1.2
AW501500	Hindmarsh River - Hindmarsh Vy Res Offtake	15.0	10.0	3.20	4.48	11.0	0.8
AW50452	Sixth Creek - Castambul	15.0	14.0	3.30	5.15	6.0	4.3

5. Modelling Approach

5.1. Pre-Burst

Pre-burst rainfall is incorporated into 2 event types considered in this study: Burst plus pre-burst and complete storm. For the Burst plus pre-burst method the pre-burst is subtracted from the storm initial loss. The storm initial loss was previously determined for the test catchments in ARR Project 6. If the pre-burst is more than the storm initial loss it is not added into the burst temporal pattern. However this could be addressed with a simple pre-burst pattern. If the pre-burst is less than the storm initial loss the remaining storm initial loss is taken off the burst pattern.

A complete storm approach adopts the temporal pattern from the entire storm event, therefore intrinsically including pre-burst rainfall. The initial loss applied to a storm event is also the storm initial loss calculated for historic events as a part of ARR revision Project 6. The estimation of pre-burst rainfall is discussed in detail in Part 2 of this report (Loveridge et al. 2015).

The median pre-burst value at the location is sampled from a grid of pre-burst to burst ratios. Grids of the pre-burst to burst ratio were developed for the 50%, 5% and 1% AEP for durations 60, 180, 360, 720, 1440, 4320 minutes and interpolated between. The pre-burst ratio distribution for the region is then scaled by the median at the point location.

5.2. Event Loading

Burst loading refers to the distribution of rainfall within a burst and is a defining characteristic of a rainfall event. The burst loading is the time during which the heaviest rainfall occurs within a burst event. Three types of loading are typically considered, ‘front’, ‘middle’ and ‘back’ loaded events (refer to Figure 5).

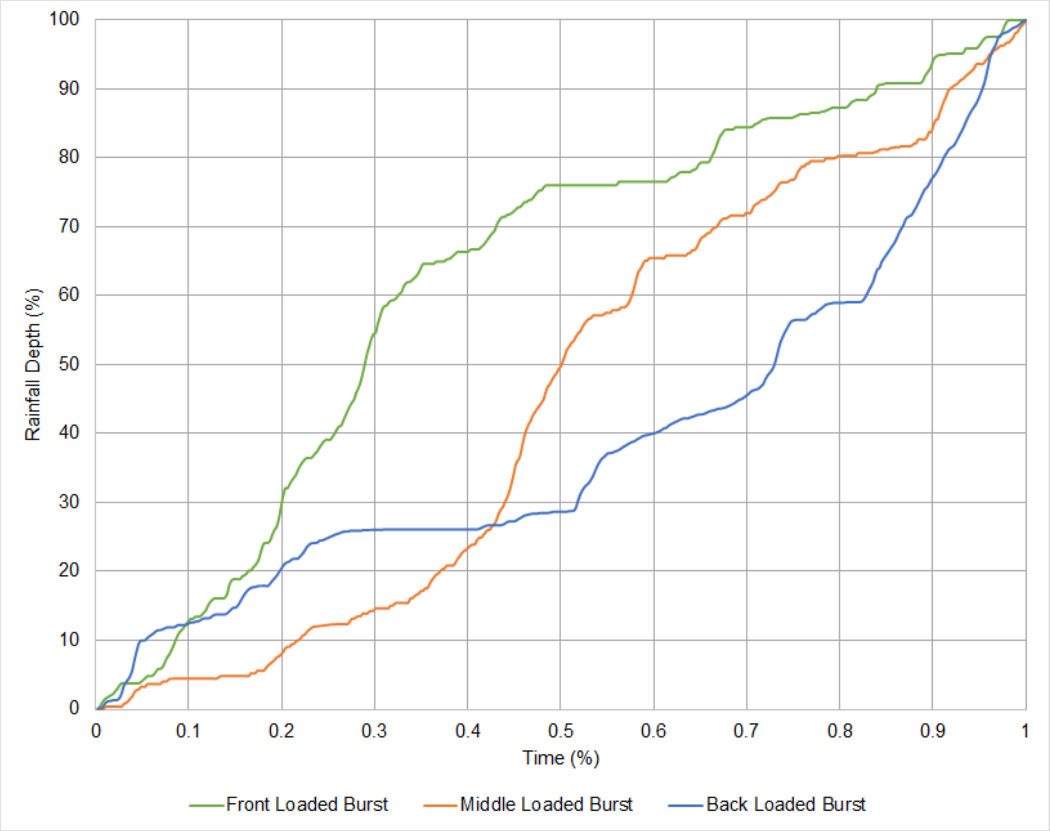

Figure 5: Example Front Middle and Back Loaded Events

The loading has been determined for each event in the event database. Each event is given a burst loading depending on when 50% of the total rainfall occurs. Events are categorised on where 50% of the burst rainfall occurs:

- front loaded – 0-40% of the time,
- middle loaded – 40-60% of the time, and
- back loaded – 60-100% of the time.

Different regions' burst loading distribution has been derived by examining the event database in that region with respect to burst loading and duration. Each region is then characterised by its burst loading distribution, which describes the percentage of front, middle and back loaded events for different durations. The ratio of front/middle/back for each region was determined for less than and greater than 6 hours (Table 6). The ratio was assumed to be constant across all AEPs.

Table 6: Burst loading by region and duration

Region	Duration Bin	Front Loaded (%)	Middle Loaded (%)	Back Loaded (%)
Southern Slopes (Tasmania)	≤ 6hr	21.5	64.1	14.4
	> 6hr	20.5	60.0	19.5
Southern Slopes (mainland)	≤ 6hr	30.1	53.0	16.9
	> 6hr	22.7	53.7	23.6

Murray Basin	≤ 6hr	28.3	53.8	17.9
	> 6hr	24.7	52.5	22.7
Central Slopes	≤ 6hr	31.0	53.3	15.7
	> 6hr	27.0	46.9	26.1
East Coast South	≤ 6hr	26.5	57.1	16.4
	> 6hr	17.1	58.6	24.3
East Coast North	≤ 6hr	28.9	56.5	14.6
	> 6hr	23.4	48.5	28.1
Wet Tropics	≤ 6hr	16.0	71.8	12.2
	> 6hr	18.7	58.1	23.2
Monsoonal North	≤ 6hr	27.6	63.7	8.8
	> 6hr	27.5	41.4	31.2
Rangelands West	≤ 6hr	23.7	62.5	13.8
	> 6hr	23.6	49.2	27.2
Rangelands	≤ 6hr	29.0	56.6	14.3
	> 6hr	24.4	49.2	26.4
Southern and South Western Flatlands (West)	≤ 6hr	30.8	49.3	19.9
	> 6hr	31.4	48.9	19.7
Southern and South Western Flatlands (East)	≤ 6hr	27.6	52.4	20.0
	> 6hr	17.4	54.4	28.2

5.3. Ensembling

In order to test the temporal pattern sampling methods an ensembling framework was developed. An ensemble of design rainfall events is produced for each test catchment. The ensemble samples variability in temporal patterns (and hence rainfall intensities), event duration, pre-burst rainfall (where applicable) and initial loss. Continuing loss remained constant across the events.

For each catchment 10 temporal patterns were chosen for each sampling method. A total of 200 events were run which sampled from these 10 temporal patterns 20 times. While 10 events could have been run, 200 were used to account for the variability in initial loss and pre-burst and avoid the random sampling of the initial loss and pre-burst influencing the results.

Events are selected for both the ROI and Region approach based on the regional burst loading. If there are not enough events to reproduce the region loading ratios events were selected randomly. When selecting events the ratios were rounded up to ensure at least 1 of each loading was selected.

For each location of interest the median pre-burst at the site is calculated from a grid. The median pre-burst curve for the region the location is within is scaled by the at site median. For the ensemble the pre-burst ratio is randomly sampled from the standardised distribution for the region the catchment is within (Refer to Part 2 report). As the burst rainfall depth is already know the pre-burst depth can be calculated. For complete storm when event is scaled the pre-burst is scaled by same ratio as the storm. Initial and continuing losses are applied as per ARR Project 6 (Table 5).

Six flood quantiles (50%, 20%, 10%, 5%, 2% and 1% AEP) were run with 200 events per quantile. Intensity Frequency Duration (IFD) data was based on the Bureau of Meteorology 2013 IFDs. An ensemble of 200 events is run for each duration, of which there are nine (1, 2, 3, 4.5, 6, 9, 12, 18, 24hour). IFDs values were interpolated for non-standard durations (used in the ROI approach). Areal Reduction factors were calculated depending on the duration and AEP of interest based on the ARR Project 2 (Jordan et al, 2013) formulae and applied to the IFD depths.

Design rainfall events are input into a hydrologic model of each catchment, and a series of design peak flows are estimated. The maximum flow for each quantile (based on the mean flow for each duration) is then determined and plotted against flows produced by a flood frequency analysis (FFA) of each catchment’s historical record. The critical duration may change between quantiles. Baseflow is added to the estimated flow prior to comparison with the FFA.

Table 7 summarises the inputs and assumptions in the modelling.

Table 7: Inputs to Ensemble

Method		Inputs/Assumptions						
		Temporal Pattern Selection	**Number of Patterns**	**Initial Loss**	**Continuing loss**	**Event Loading F/M/B**	**Pre-burst**	**Selection of Events (random/fixed)**
ROI	**Burst**	Selected for each AEP based on: IFD similarity of location of pattern compared to the target Distance of location of pattern to the target The AEP of the event (calculated based on the target IFD) compared to the AEP required	10	P6 Burst loss with a standardised loss distribution	Median of P6 Calibrated Data equivalent 5min value	Region based-burst loading	N/A	Initial Loss sampled 200 times from distribution 10 temporal patterns sampled 20 times
	Pre-burst plus Burst			P6 Storm Loss with a standardised loss Distribution			Distribution from Region, AEP and Duration	Initial Loss sampled 200 times from distribution 10 temporal patterns sampled 20 times Pre-burst sampled 200 times from distribution
	Complete Storm			P6 Storm Loss with a standardised loss Distribution			Embedded in Storm	Initial Loss sampled 200 times from distribution 10 temporal patterns sampled 20 times
Region	**Burst**	Three AEP bins: rare, mid and frequent. Rare and mid bins selected randomly from patterns in the region within the bin Frequent bin takes top 10 patterns to avoid selection of very frequent events (1 EY events)		P6 Burst loss with a standardised loss distribution			N/A	Initial Loss sampled 200 times from distribution 10 temporal patterns sampled 20 times
	Pre-burst plus Burst			P6 Storm Loss Distribution			Distribution from Region, AEP and Duration	Initial Loss sampled 200 times from distribution 10 temporal patterns sampled 20 times Pre-burst sampled 200 times from distribution

6. Testing of Methods on Test Catchments

In order to test the temporal pattern sampling methods an ensemble of events selected by each method was compared to flood frequency analysis for 35 test catchments.

6.1. Inputs

Figure 6 shows the regions of influence for the each of the test catchments. The catchments near the coast contain a smaller potential region as they may contain a large amount of ocean. However much of the coast contains a high pluviograph density. Figure 7 depicts the location of the test catchments on the temporal pattern regions map. For some locations like South West WA the ROI and region zones are very similar. The total number of pluviograph stations and events per sampling method for each catchment is summarised in Table 8. Other inputs and parameters adopted for the test catchments are documented in Table 5.

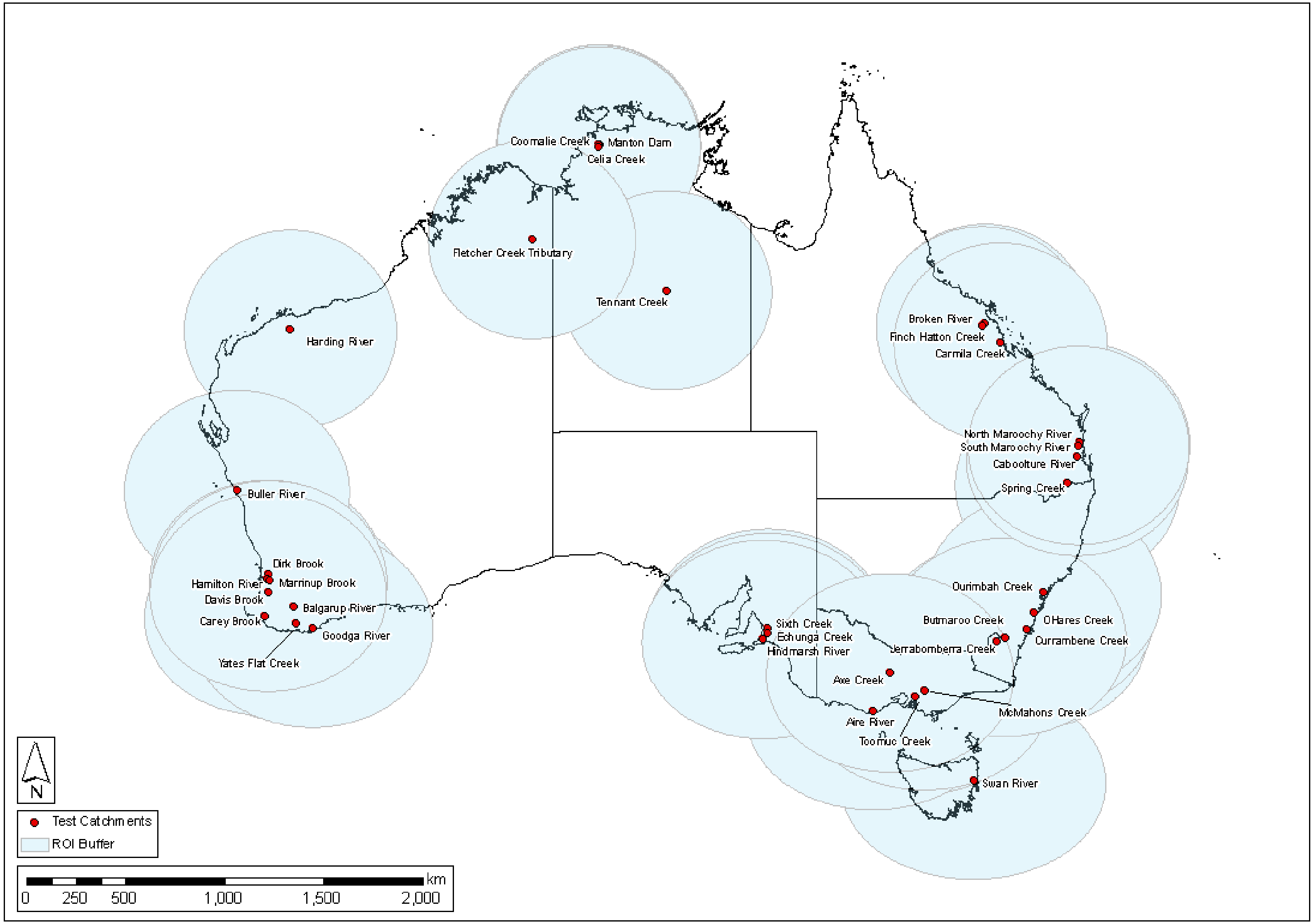

Figure 6: Test Catchments Region of Influence

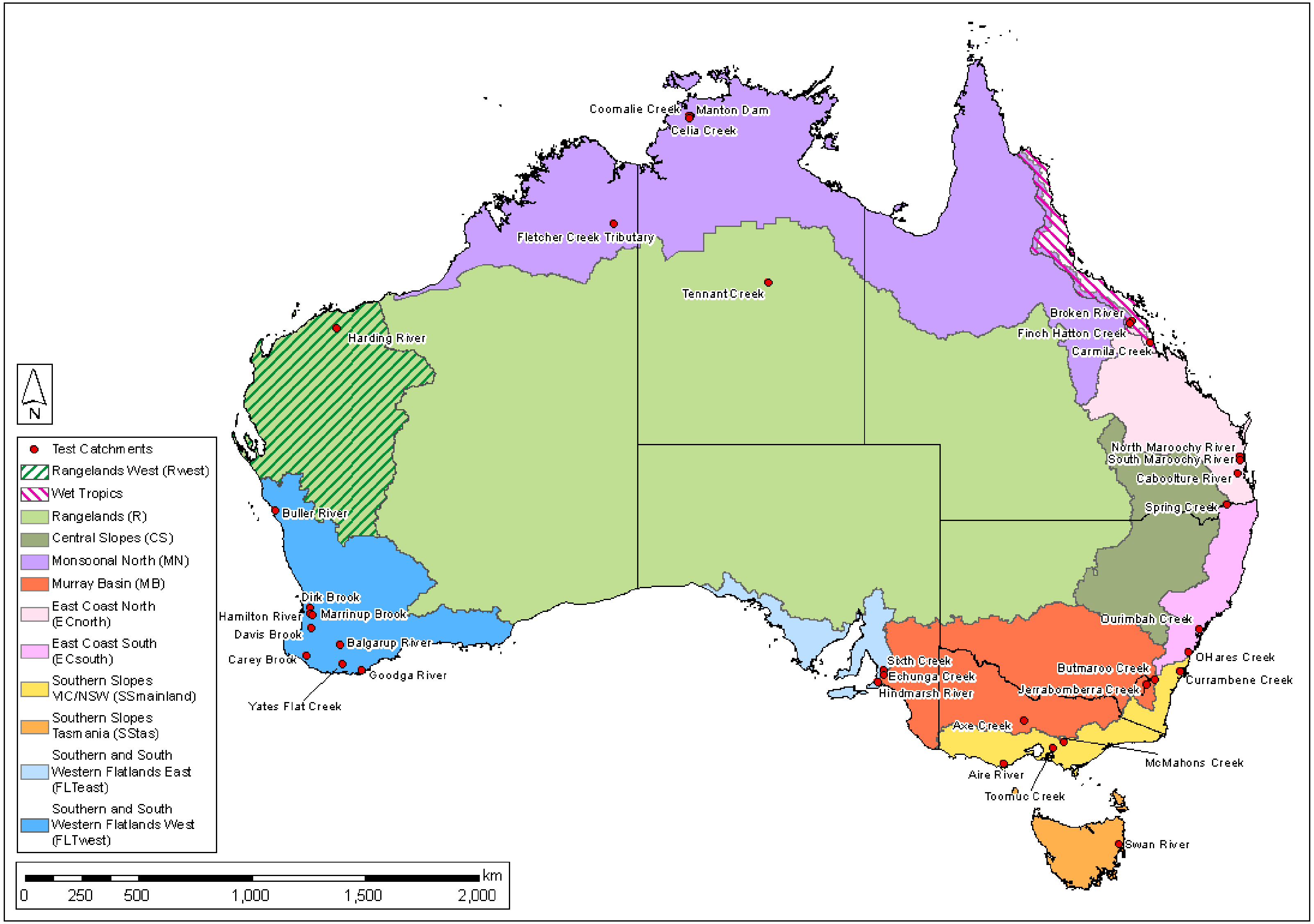

Figure 7: Test Catchments on Map of Regions

Table 8: Test Catchment – Number of pluviographs and events by sampling method

Catchment	ROI		Region	
	Pluvios within 500km radius	**Events**	**Pluvios within region**	**Events**
Swan River u/s Hardings Falls	210	8715	110	3477
Aire River - Wyelangta	493	26968	356	20581
Currambene Creek - Falls Creek	568	38888	356	20581
McMahons Creek - u/s Weir	623	38871	356	20581
Toomuc Creek - Pakenham	607	37860	356	20581
Axe Creek - Sedgewick	524	35194	233	18399
Butmaroo Creek - Butmaroo	746	49262	233	18399
Jerrabomberra Creek - Four Mile Creek	775	50659	233	18399
Spring Creek - Killarney	392	23557	118	7167
O'Hares Creek - Wedderburn	563	38072	331	19856
Ourimbah Creek - u/s Weir	555	37648	331	19856
Caboolture River - Upper Caboolture	357	21111	210	12123
North Maroochy River - Eumundi	338	19815	210	12123
South Maroochy River - Kiamba	342	20005	210	12123
Carmila Creek - Carmila	162	8416	99	5437
Finch Hatton Creek - Dam Site	160	8660	99	5437
Broken River - Old Racecourse	160	8668	211	12287
Celia Creek - u/s Darwin R Dam	71	4153	211	12287
Coomalie Creek - Stuart HWY	72	4182	211	12287
Fletcher Creek Trib. - Frog Hollow	87	5280	211	12287
Manton River u/s Manton Dam	70	4113	211	12287
Harding River - Marmurrina Pool U-South	97	5594	93	5391
Tennant Creek - Old Telegraph Stn	57	3051	226	12618
Balgarup River - Mandelup Pool	322	24564	349	26402
Buller River - Buller	171	12118	349	26402
Carey Brook - Staircase Rd	319	24349	349	26402
Davis Brook - Murray Valley Plntn	330	25037	349	26402
Dirk Brook - Kentish Farm	345	26000	349	26402
Goodga River - Black Cat	320	24314	349	26402
Hamilton River - Worsley	338	25580	349	26402
Marrinup Brook - Brookdale Siding	340	25729	349	26402
Yates Flat Creek - Woonanup	321	24430	349	26402
Echunga Creek u/s Mt. Bold Res.	118	6920	56	3450
Hindmarsh River - Hindmarsh Vy Res Offtake	112	6607	56	3450
Sixth Creek - Castambul	113	6660	56	3450

6.2. Results

Appendix B presents the comparison of the flow estimates for each of the 5 tested sampling methods to the at-site Flood Frequency Analysis. Slightly more than half the estimates of the 1% AEP are within the confidence limits. Slightly less than half the 20% AEP estimates are within the confidence limits. The study intended to compare the results and recommend a preferred option based on its ability to match the flood frequency analysis in terms of shape, and magnitude. However it was found that the differences between the methods is generally much smaller than the difference between the estimates and the at site results. In all cases the differences between the methods is smaller than the confidence limits. At the 1% AEP quantile more than half the locations results are near identical for all methods. In other cases they are generally similar. The uncertainties in the losses were found to be influencing the results and all methods could likely fit the observed FFA with an adjustment of the loss values.

Figure 8 to Figure 9 present the FFA comparisons for Finch Hatton Creek and Dirk Brook with the maximum and minimum flows along with the mean produced for each quantile for the regional approach.

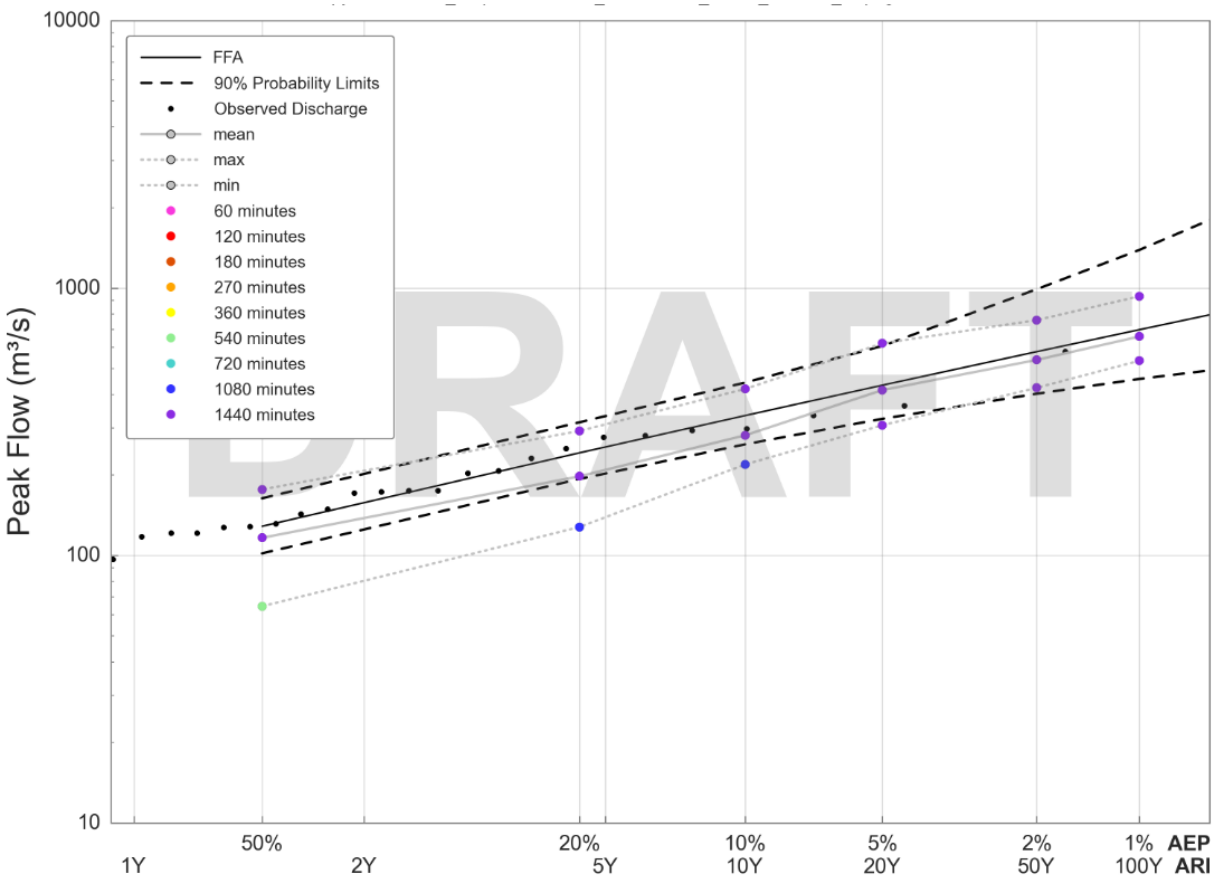

Figure 8: Mean, Minimum and Maximum flow per quantile - Finch Hatton

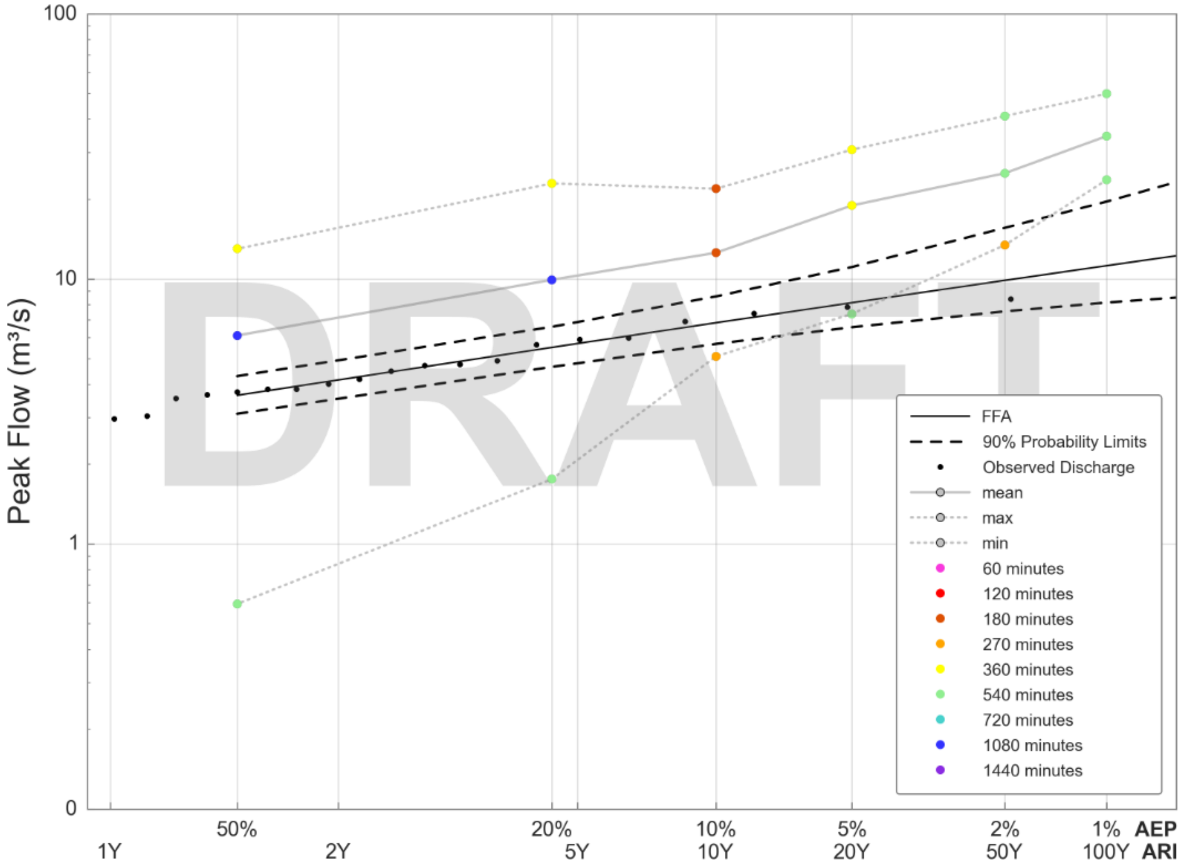

Figure 9: Mean, Minimum and Maximum flow per quantile – Dirk Brook

The Region method typically produces higher flows than the ROI approach. The storm losses developed for some catchments are considered too high, resulting in the burst approach producing higher flows than the complete storm approach. This occurs for the majority of catchments. On some catchments the burst approaches produce nearly identical results (example Jerrabomberra Creek and Manton Dam). While on other catchments the temporal pattern technique (ROI and Region) produces more similar results eg. Broken River and Caboolture River.

At the 10% AEP event the ROI approach for Davis Brook, Murrinup Brook and Carey Brook catchments produces similar or lower results than the 20% AEP. This leads to a step in the flood frequency analysis.

For Broken River (Figure B18), the FFA curves produced by the ROI are distinctly different from those produced by the regions. Appendix C depicts the location of the events chosen by the region and ROI. This is caused by the ROI pooling events from mainly the east coast of Australia from the wet tropics area, while the Region (Monsoon North) chooses events from the top end near Darwin.

Appendix C depicts the events chosen by the ROI compared to those selected by the Region approach for a number of catchments:

- Finch Hatton Creek
- Sixth Creek
- Manton River
- Swan River
- Broken River

Swan River samples events from only Tasmania in the region approach while in the ROI approach it samples events from mainland Australia and Flinders Island. Mass curves for these events are presented in Figures C6-C12.

7. Sensitivity Testing

Sensitivity analysis was undertaken on various assumptions in the chosen approach, in order to validate the assumptions made, further optimise the method and generally test the approach's robustness.

7.1. Ensemble size

The number of events in an ensemble can lead to a biased estimate if not enough events are run. With a very large sample, events become redundant as they do not improve the accuracy of the results, and the processing time can become excessive. The ensemble size was varied in order to test the sensitivity of the peak flow estimates to increasing or decreasing the sample size. An ensemble size of 10 and 200 were tested. For Tennant Creek the ensemble size had no effect on the peak flow (Figure 10). An ensemble of 10 resulted in slightly higher flows for some catchments for example Butmaroo Creek (Figure 11) and Manton Dam (Figure 12). An ensemble size of 200 was consider sufficient for this study. In practice a sample of 10 could be used.

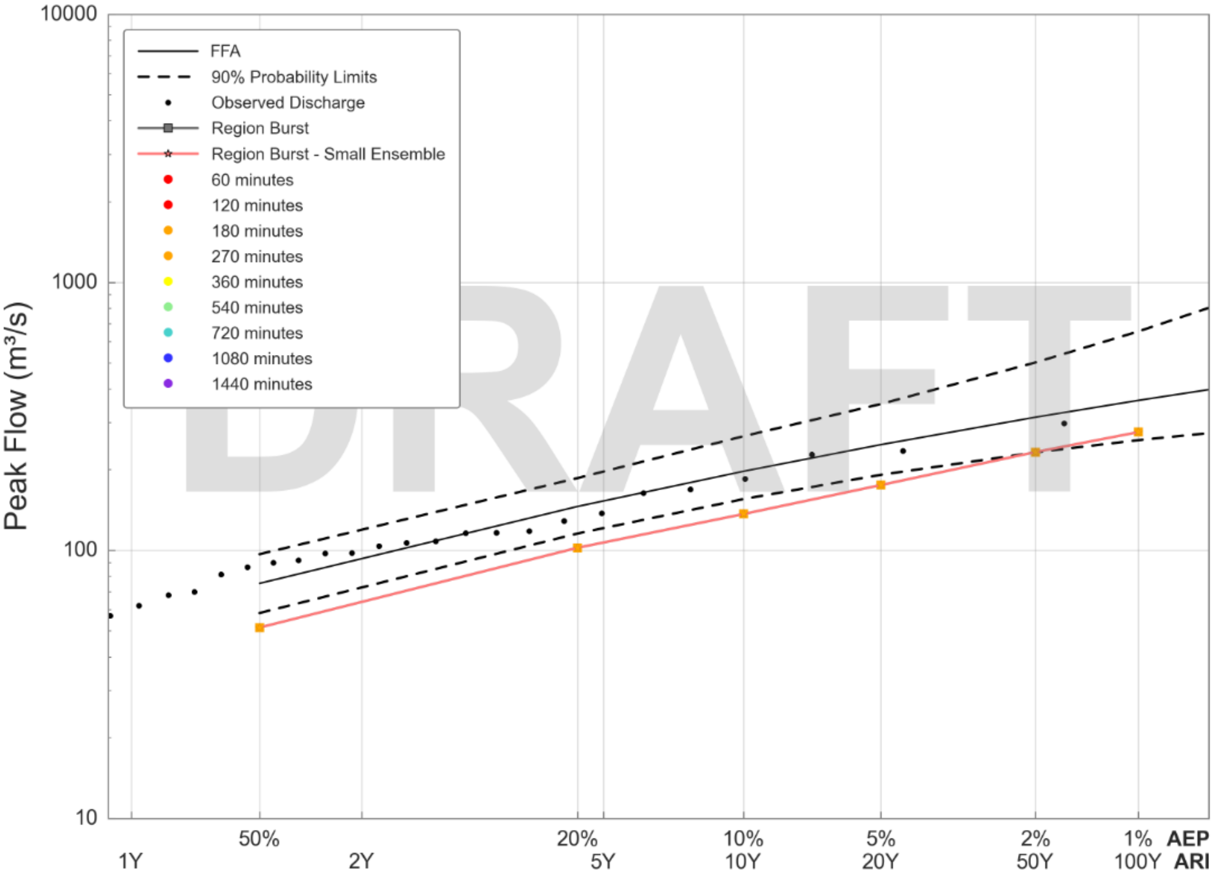

Figure 10: Effect of ensemble size- Tennant Creek

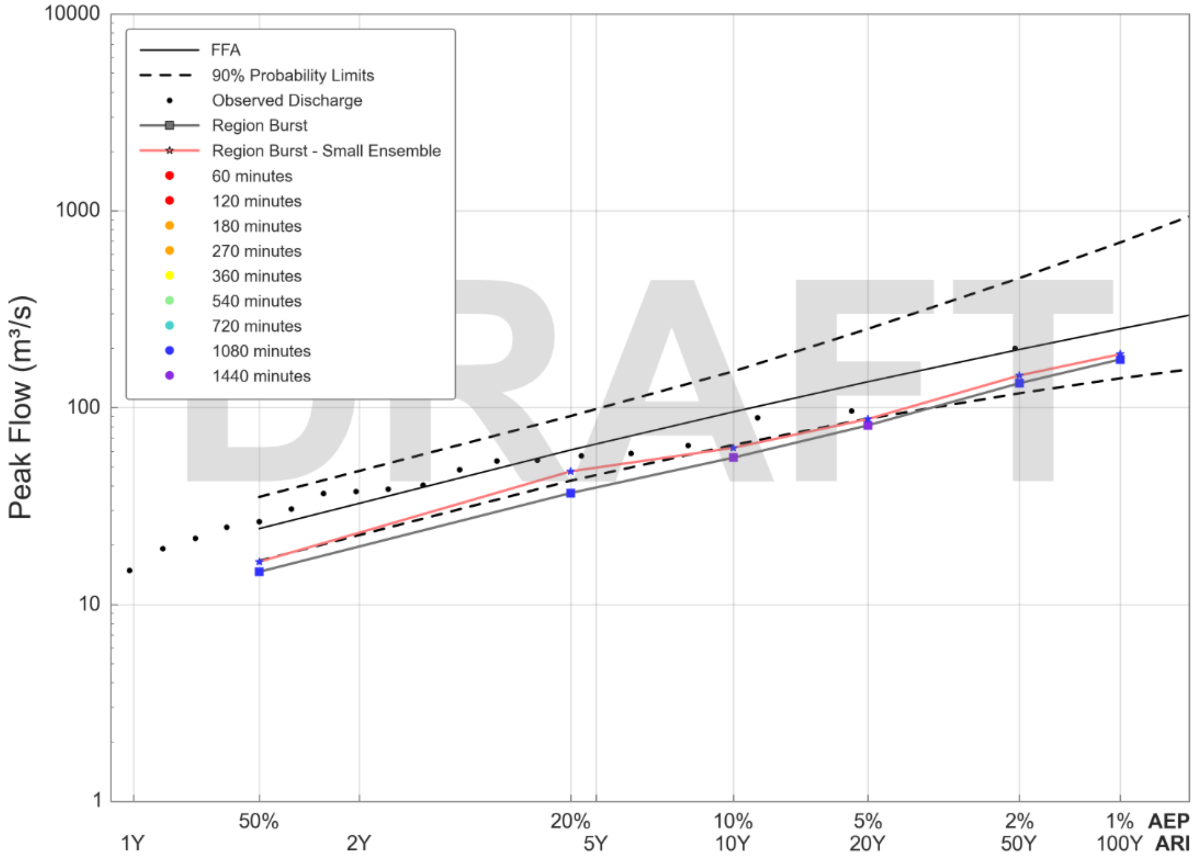

Figure 11: Effect of ensemble size – Butmaroo Creek

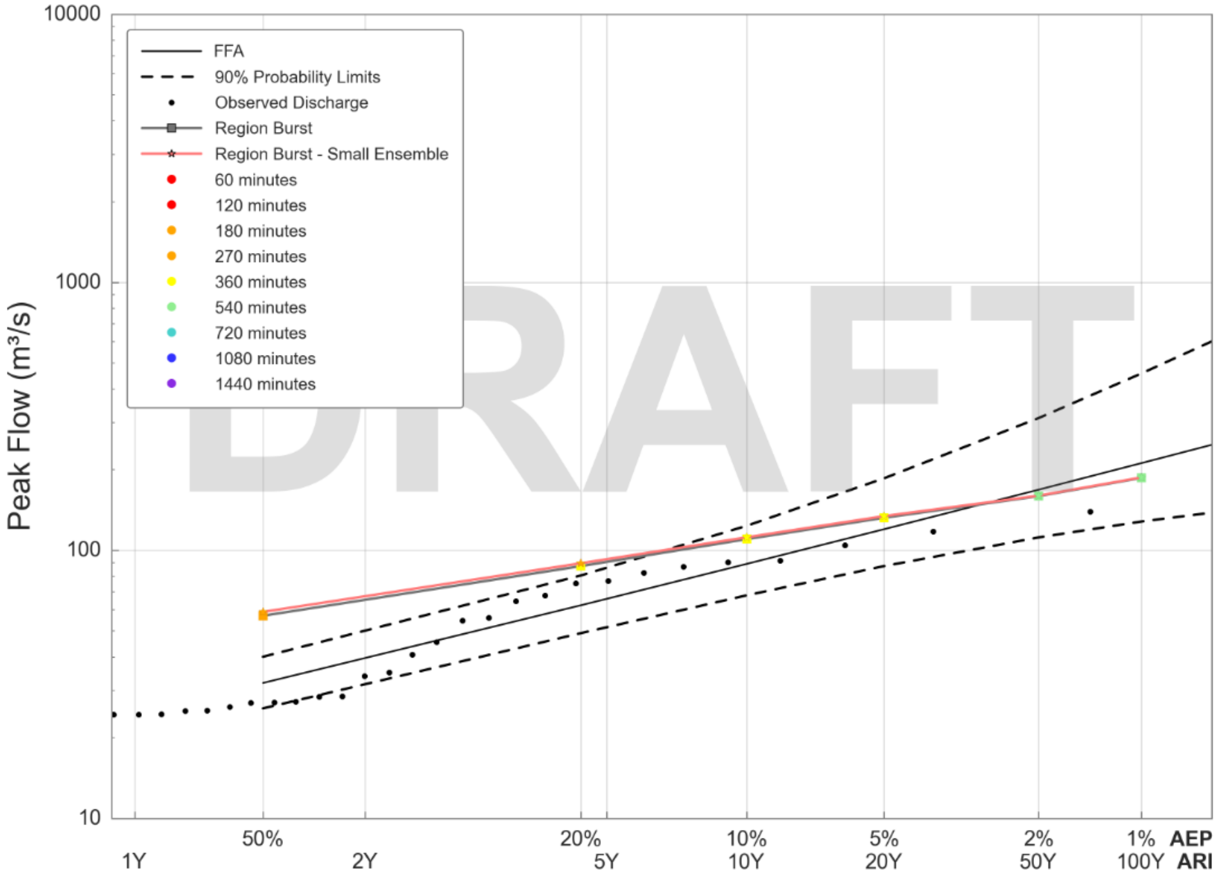

Figure 12: Effect of ensemble size - Manton Dam

7.2. IFD

The study adopted the catchment centroid IFD value based on the BoM 2013 IFDs. Given the size of the test catchments it was considered that there was unlikely to be a large variation in IFD across the catchment and the centroid value would therefore be a valid representation. For Manton Dam and Yates Flat Creek the ensemble was run with the centroid, catchment average IFD and at site IFD to determine if this was likely to impact results. Figure 13 shows that the centroid IFD produced a higher flow in this case. The catchment average IFD produced the lowest results. Figure 14 presents the results for Yates Flat Creek.

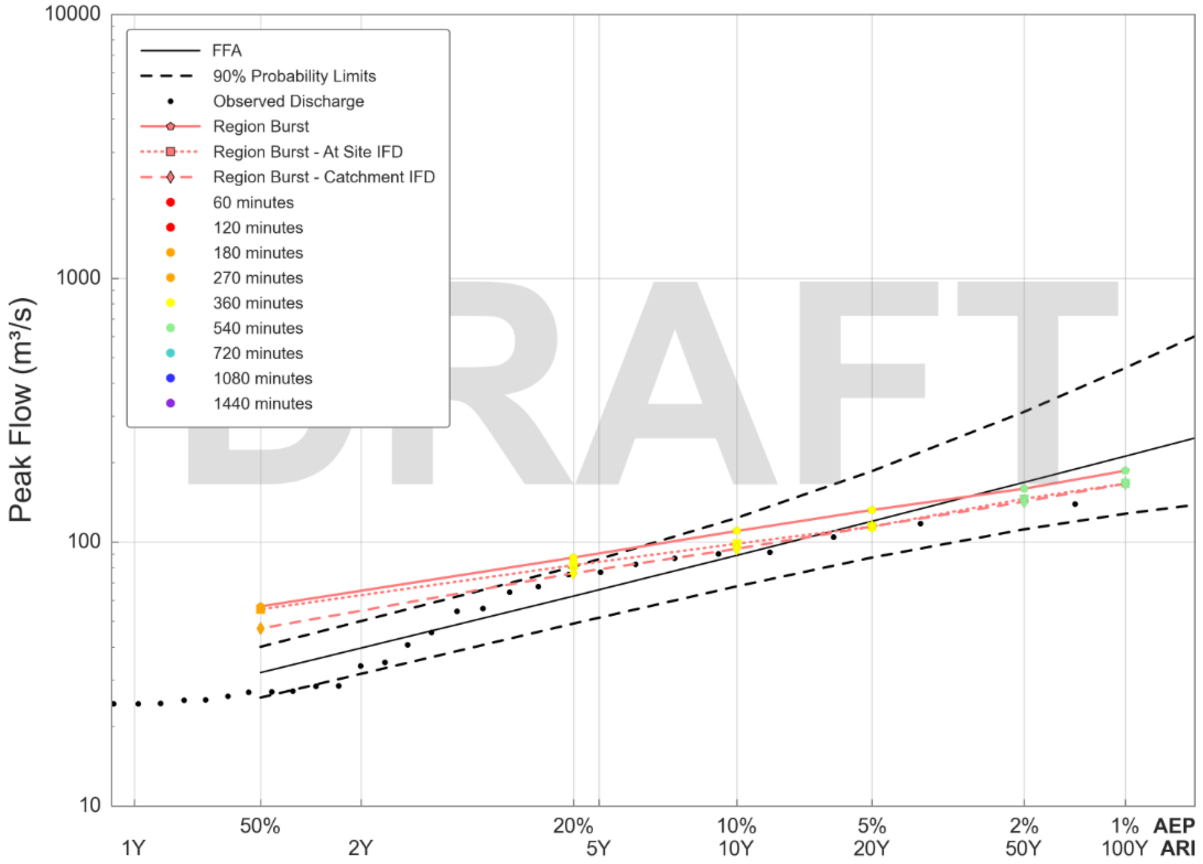

Figure 13: Effect of using centroid vs catchment average vs at site IFD- Manton Dam

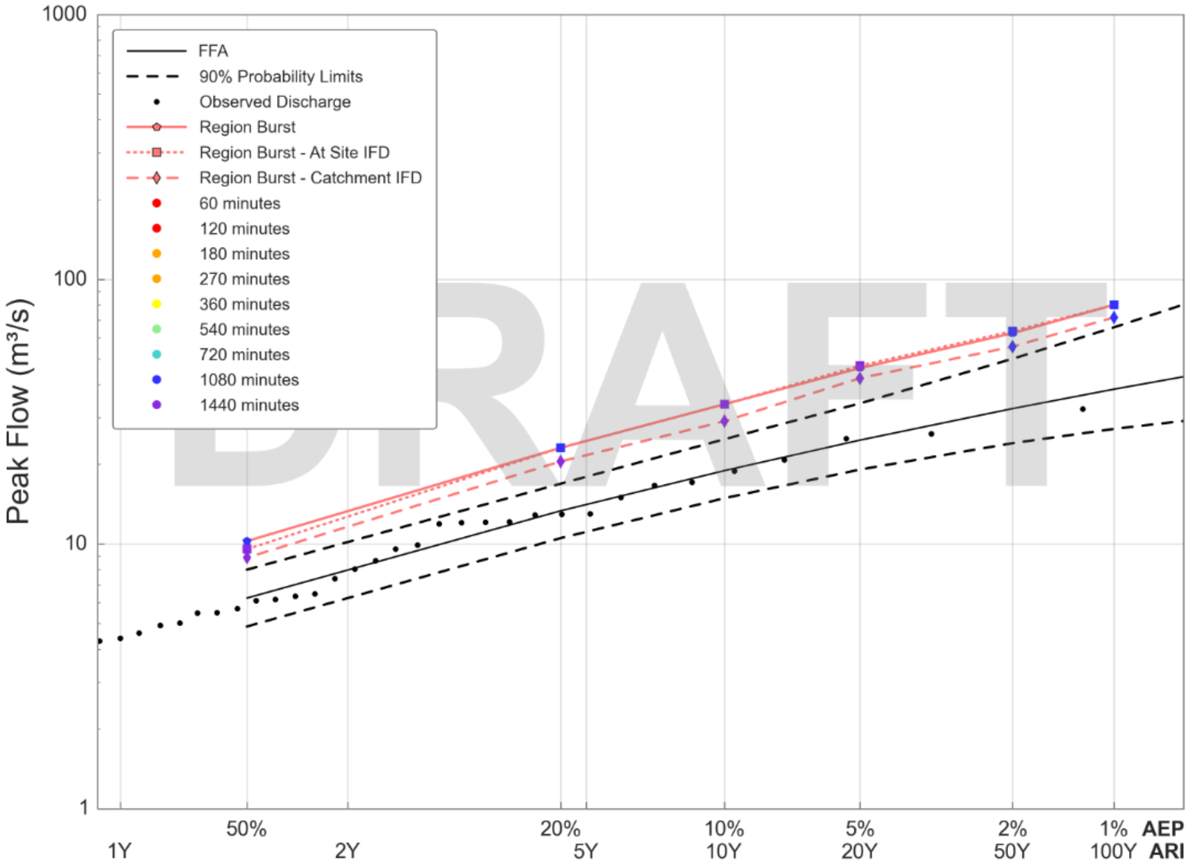

Figure 14: Effect of using centroid vs catchment average vs at site IFD – Yates Flat Creek

7.3. Region Temporal Pattern AEP bins

For the region approach, the scaling of very frequent patterns was found to have an effect on the peak flow. It was found that often when a 1 EY event at the donor location transferred to the test location it was more frequent than a 1 EY event. These events were then being scaled to a 20% AEP event. This resulted in flood quantiles at the interface of the mid and frequent bins giving contradictory estimates i.e. The 20% AEP flow was larger than the 10% AEP flow.

The effect of the AEP bins adopted for the regional approach was tested. A number of ensembles were run using the:

- Frequent regional patterns for the frequent events,
- Mid-range (14.4%-3.2% AEP) regional patterns for the frequent events (More frequent than 7.2 years ARI (14.4% AEP)),
- Frequent regional patterns for the mid-range AEPs, and
- Using the top 10 patterns in the frequent range for the frequent events

Figure 15 and Figure 16 depicts the results from the testing for Yates Flat Creek and McMahons Creek. Using the frequent bin for mid-range events increased the flows and produced a bumpy

FFA curve. Using the mid-range bin for frequent events and using the top 10 events for the frequent events produced similar FFA curves. The use of the top 10 patterns in the frequent range for frequent events (up to 14.4% AEP) was adopted as it resulted in a smoother flood frequency curve. For Swan River there was little effect.

These results suggest that event scaling is the reason why the region method has tendency to produce higher flow estimates as the ROI approach minimises scaling.

7.4. Number of Patterns Sampled

The adopted approach selects 10 temporal patterns and samples these randomly to make 200 events. The effect of selecting 20 temporal patterns was tested and found to have minimal impact of flow estimates. The effect of the number of selected temporal patterns is shown on Figure 17 and Figure 18 for McMahons Creek and Butmaroo Creek respectively. Using 10 patterns resulted in slightly higher flows than using 20. To make sure that the random sampling didn’t affect the results a series of random seeds were used for the pre-burst which produced identical results.

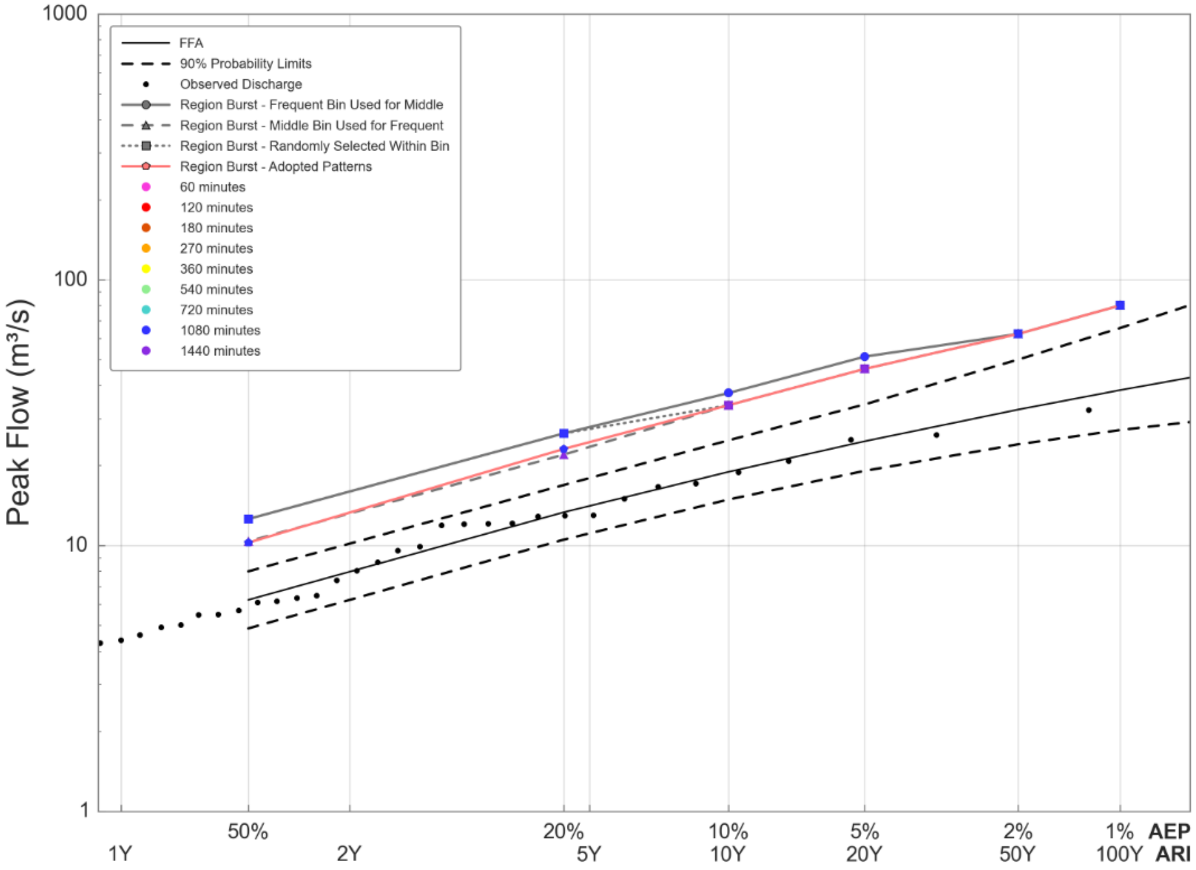

Figure 15: Effect of Region Temporal Pattern Bins – Yates Flat Creek

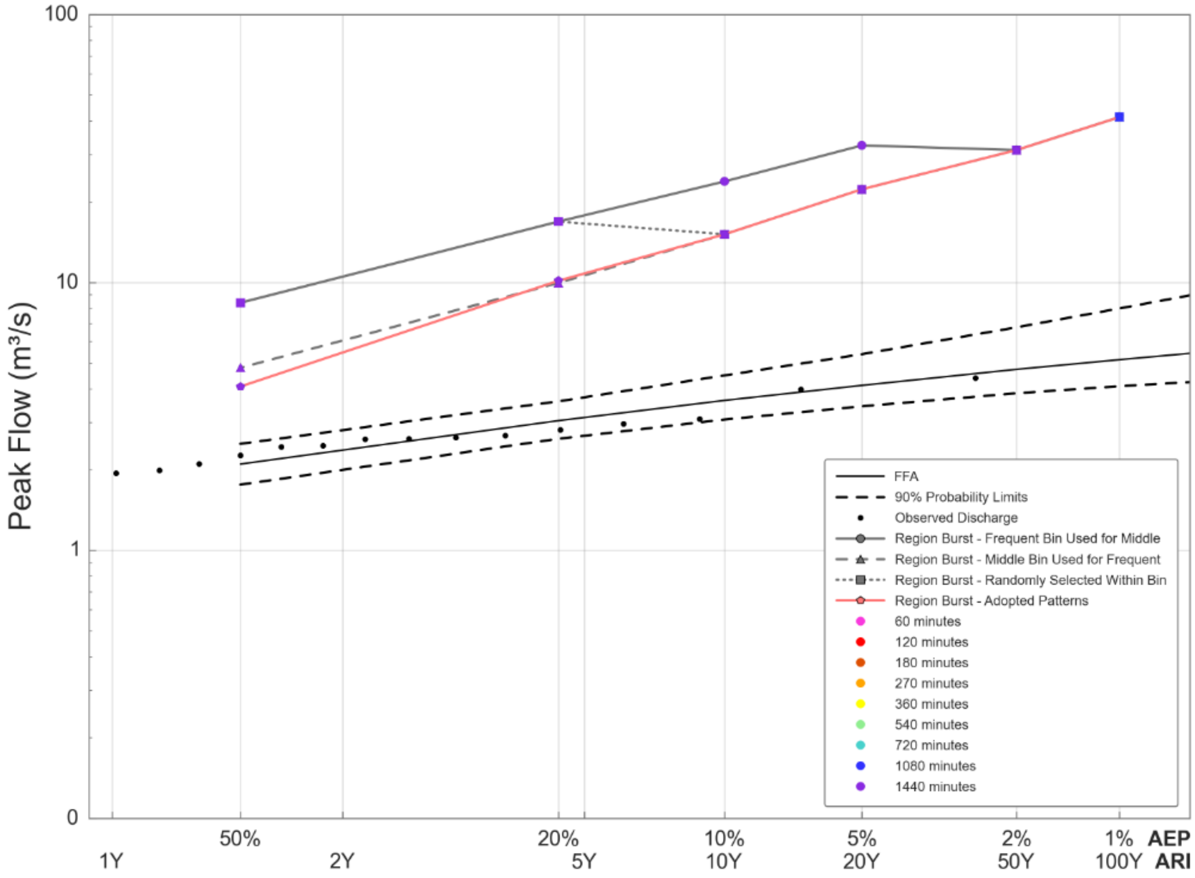

Figure 16: Effect of Region temporal pattern bins – McMahons Creek

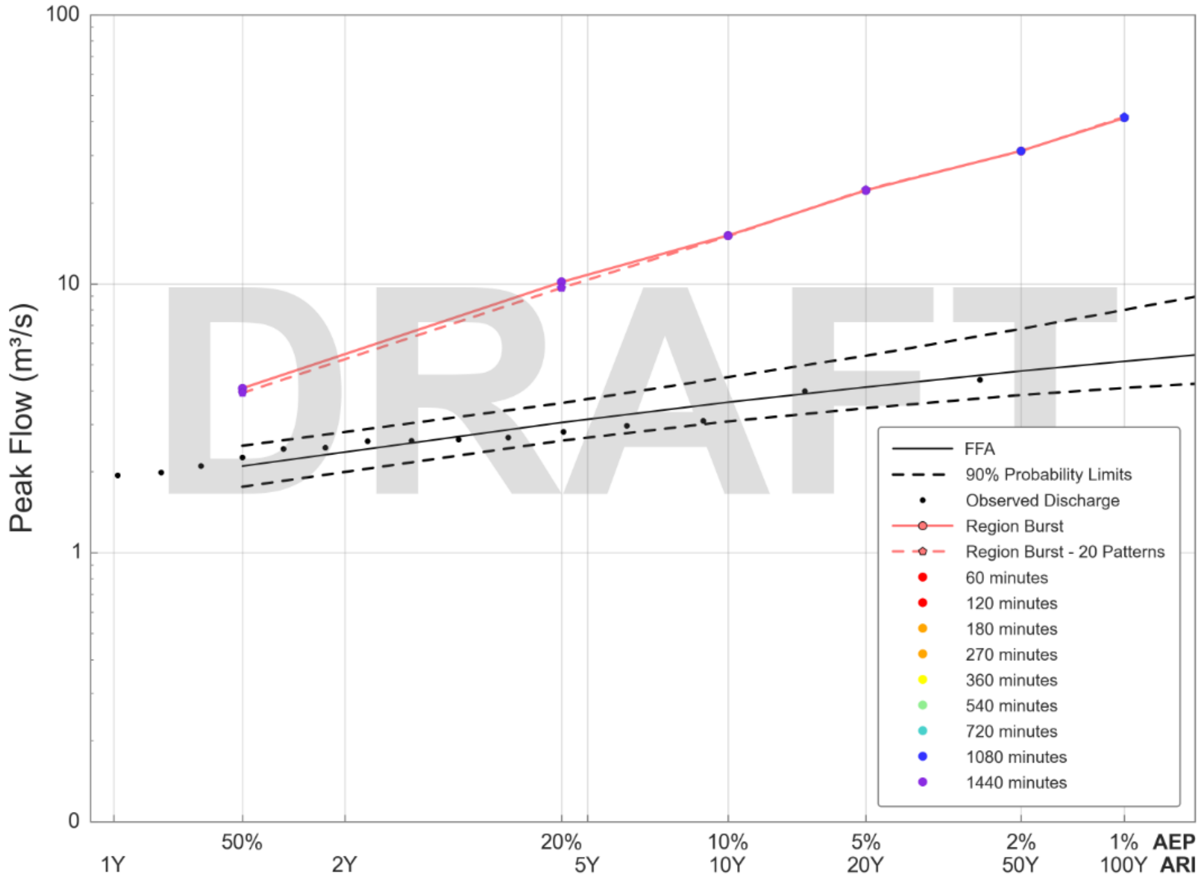

Figure 17: Effect of Number of Temporal Patterns – McMahons Creek

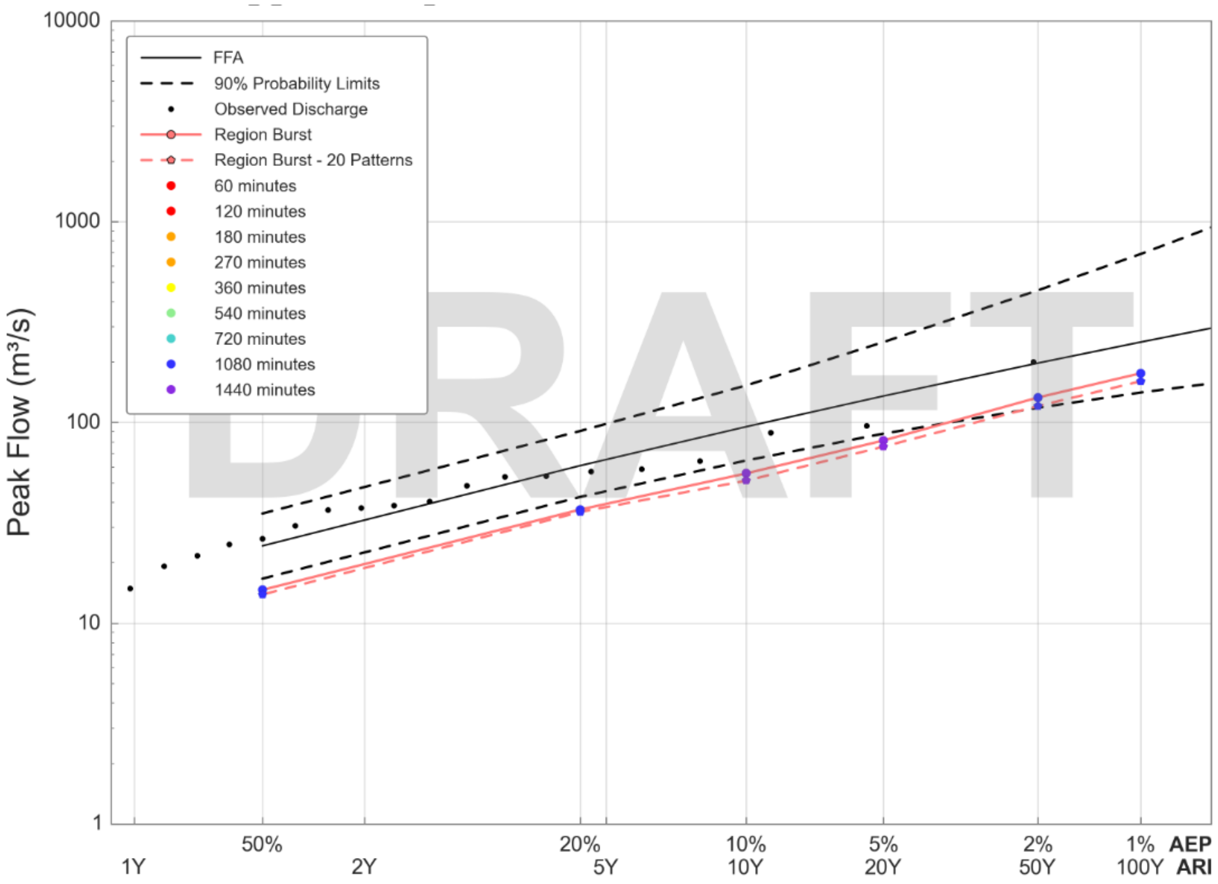

Figure 18: Effect of number of temporal patterns – Butmaroo Creek

7.5. Alternative regions

Spring Creek lies in the central slopes region close to the border of a number of regions. In order to test the sensitivity of the regions definitions, Spring Creek was run adopting temporal patterns from the following regions:

- Central Slopes,
- East Coast South,
- East Coast North, and
- Western Flatlands.

Western Flatlands is on the opposite side of the country to the Spring Creek catchment. Moving Spring Creek to other regions was found to have minimal impact on the peak flow estimates (Figure 19) but did change the critical duration.

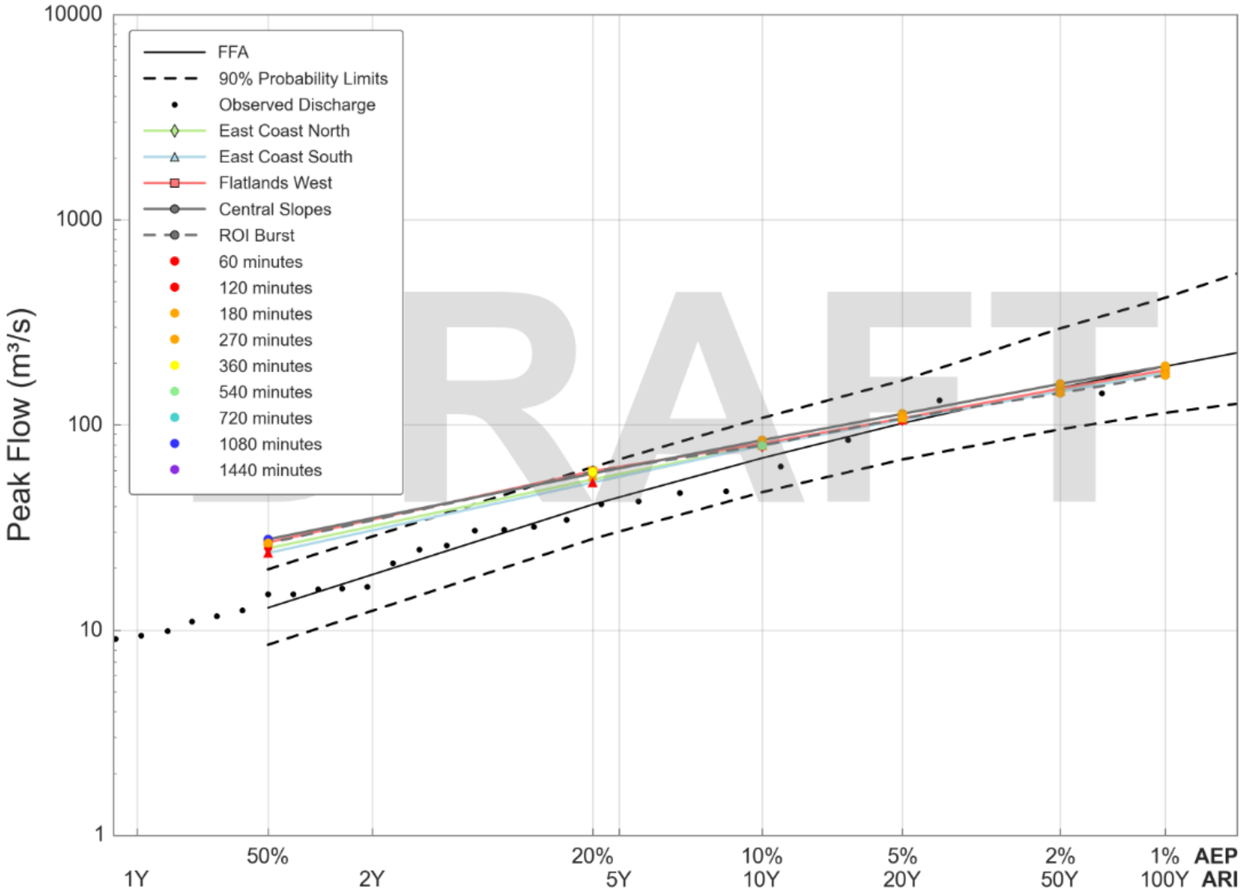

Figure 19: Effect of Alternative Regions - Spring Creek

Broken River (Figure 20) lies in the Monsoonal North region. The ensembles were run placing Broken River in the following regions:

- East Coast North

- Wet Tropics
- Flatlands West

The tested regions produced flows less than those produced by the region in which Broken River (Monsoonal North) is located. The flows produced by the alternate regions lie between the Monsoonal north region flows and the ROI flows. While Broken River is just inside the Monsoonal North region we were advised early in the study that it what just over the coastal divide and exhibited many of the characteristics of coastal catchments, yet for this catchment patterns from nearby stations produced estimates further from the FFA.

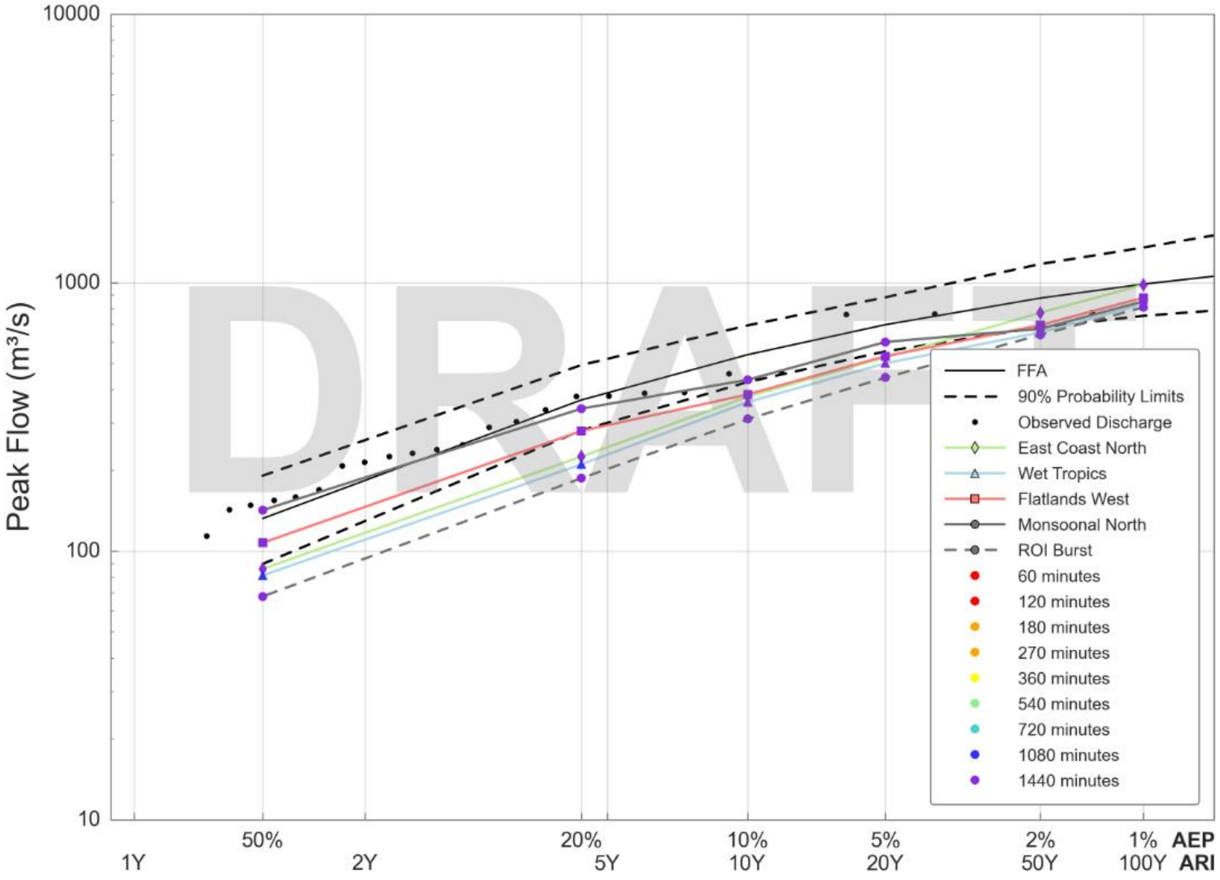

Figure 20: Effect of Alternate Regions- Broken River

7.6. Mean vs Median

The study adopted the mean peak flow estimate from each ensemble for each duration. As a sensitivity test the median was used and compared to the FFA. The effect on the quantile estimates was minimal other than on catchments with low flows particularly those with high losses. Figure 21 depicts the comparison of the quantile estimates for the mean and median approaches for Swan River and McMahons Creek catchment. For low flow catchments using the mean improved results.

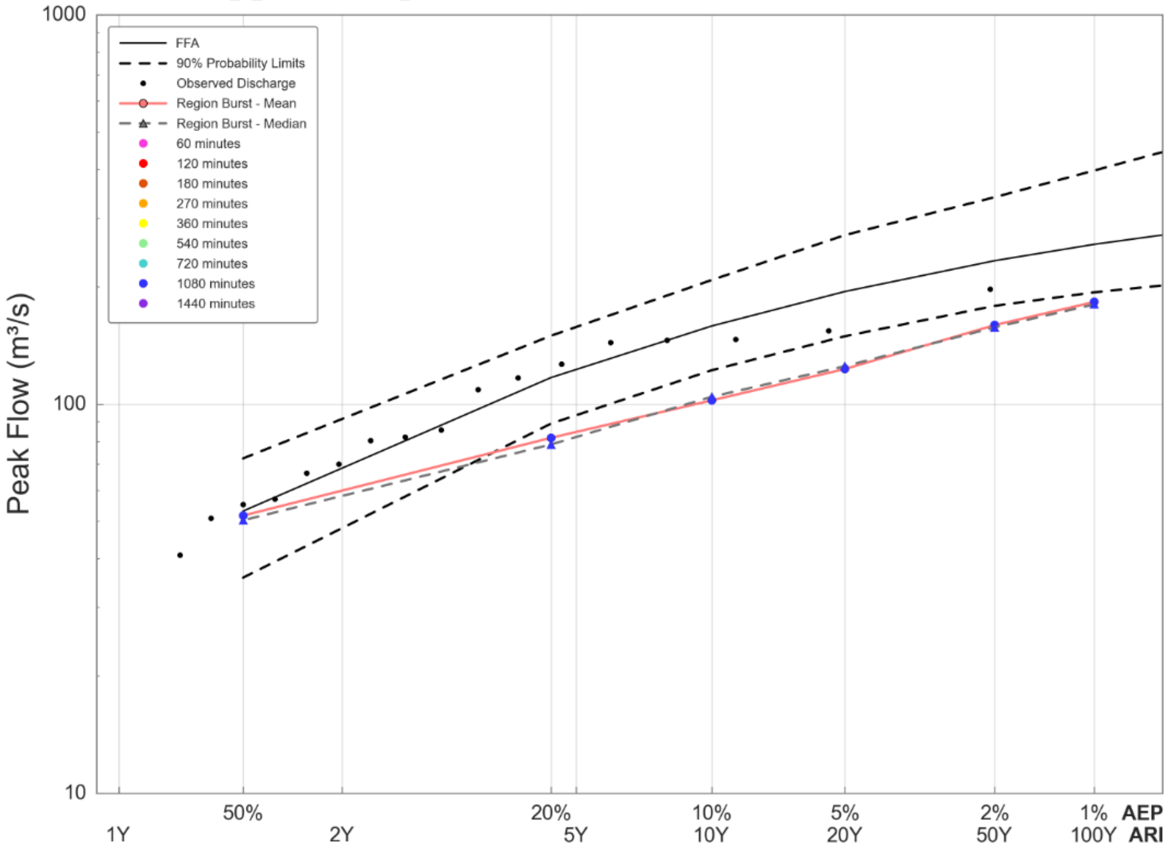

Figure 21: Effect of calculating the mean of the ensemble vs the median of the ensemble – Swan River

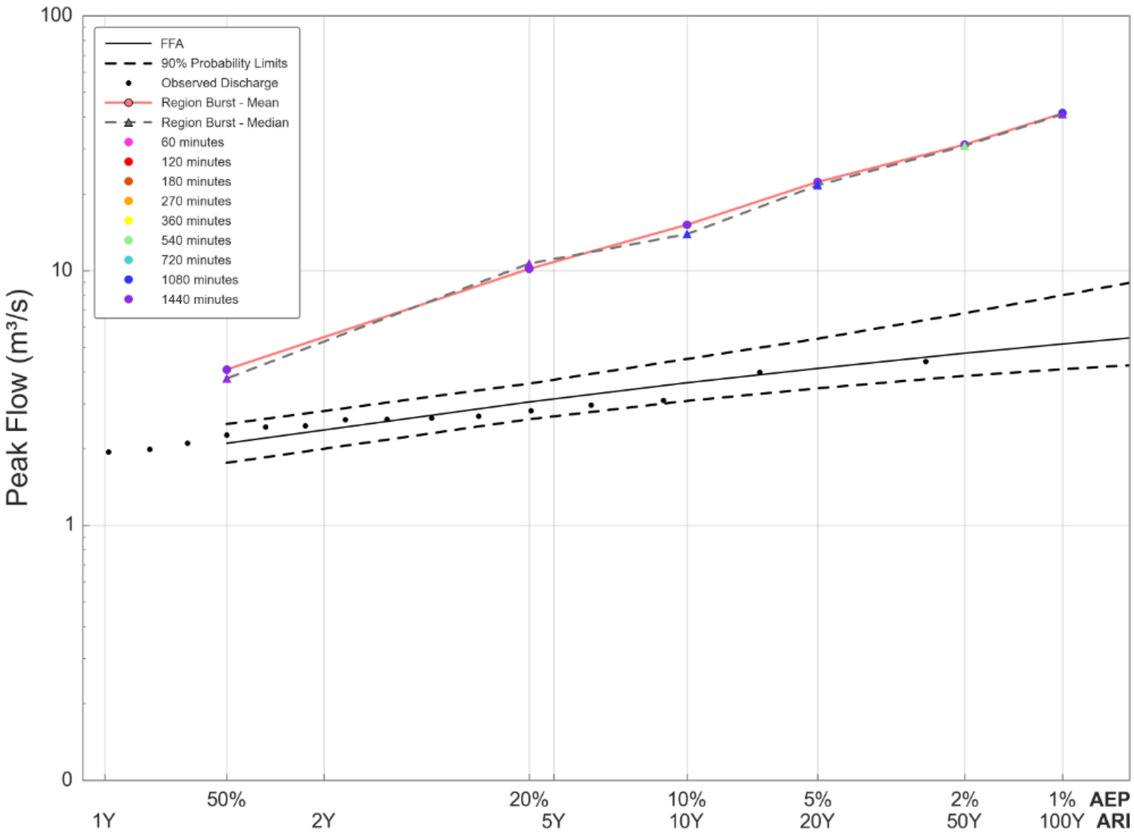

Figure 22: Effect of calculating the mean of the ensemble vs the median of the ensemble – McMahons Creek

8. Discussion and Recommendations

The testing conducted as part of this study has shown that while traditionally the temporal pattern is thought to have a large impact on flows, if an ensemble of temporal patterns are chosen the temporal patterns become less important and the losses and other factors tend to dominate.

Given the effort required in the ROI approach and the limited difference in fits to the FFA between the ROI and region approach it is considered that the Region approach should be recommended for use in Australian Rainfall and Runoff. The exact number of temporal patterns per region has not been rigorous determined, but 10 patterns seems a good compromise between numerical overhead, pattern availability and result sensitivity. In some locations a greater number would require borrowing from adjacent regions, scaling more frequent patterns up and the use of more patterns with embedded bursts.

The upscaling of patterns can produce higher flow estimates and is probably the major reason why the region method does produces slightly higher flow estimates.

Embedded bursts are possible within the chosen temporal patterns for regions. Temporal patterns were chosen based on loading and the criteria described in Section 3.2.2 where possible. Figure 23 depicts the ratio of the 1% AEP 24hr to the 1% 1hr rainfall for the 2013 IFD.

This map can be used to identify areas where embedded bursts are more likely (ie. In areas with a high ratio). Figure 23 depicts the ratio of the 1% AEP 24hr to the 1% 1hr rainfall for the 1987 IFD. There is more variability between the short and long duration events with the new IFD. The movement of a temporal pattern from a location with a low ratio to a location with a high ratio is likely to result in embedded bursts.

The ROI complete storm approach should be kept as an option for volume sensitive systems with high pre-bursts. This would typically be smaller catchments and urban systems.

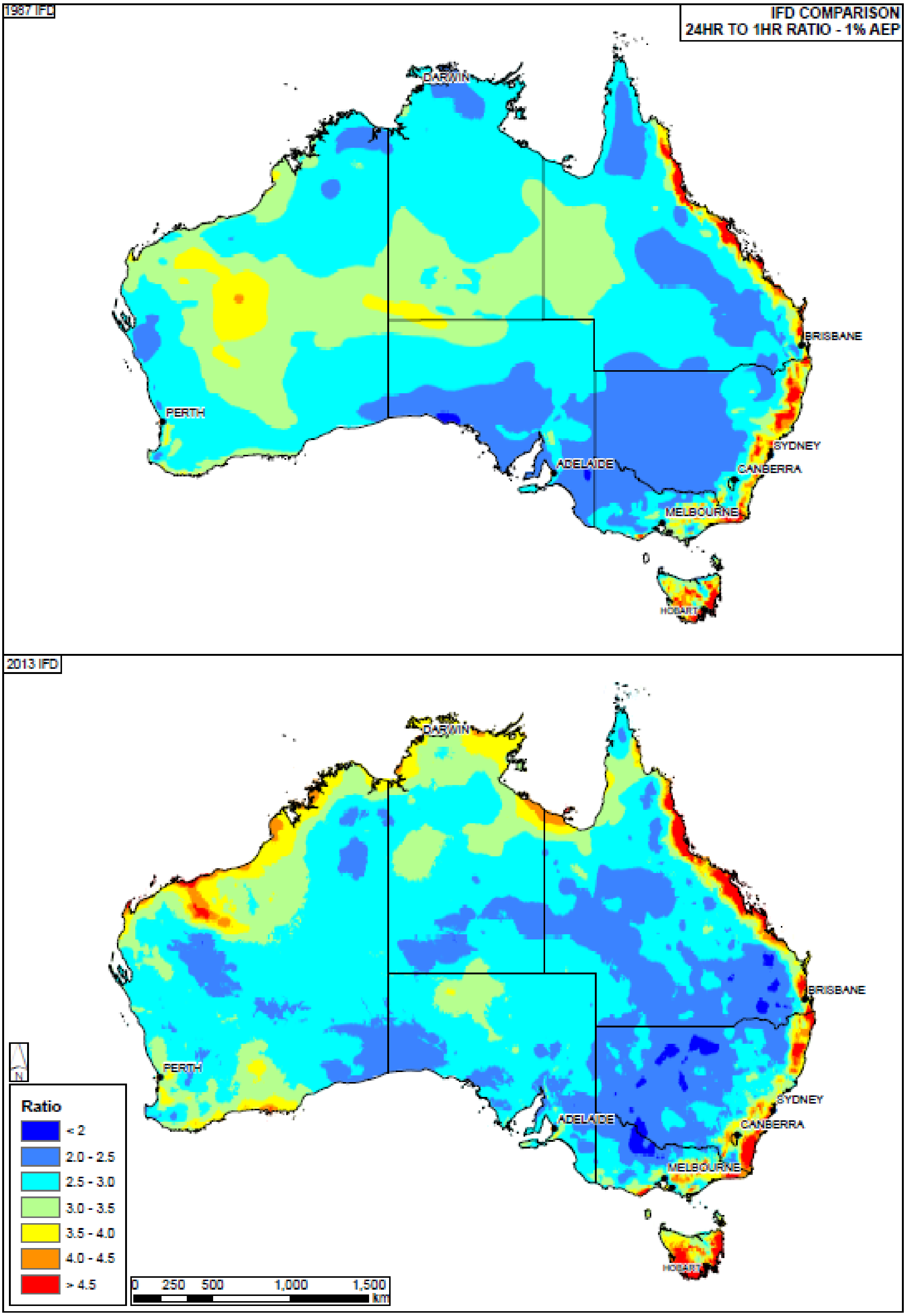

Figure 23: Ratio of the 1% AEP 24 hr to the 1% 1hr rainfall – 2013 IFD and 1987 IFD

9. Conclusions

This assessment has shown that a simple ensemble regional pattern approach using ten patterns can capture much of the variability of temporal patterns and remove much of the variability of the flow estimates. Such a pattern approach is also suitable for Monte Carlo approaches with very little additional numerical overhead.

The significant scaling up of patterns will tend to produce higher flow estimates and should be avoided where possible.

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