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Benchmarking ARR2019 for Victoria

Technical Report

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Executive Summary

Whilst considerable effort was expended in developing the new Australian Rainfall and Runoff (ARR) 2019 guidance, there was limited opportunity for benchmarking how the different combinations of design inputs impacted on the design flood estimates. After the release of ARR2019, studies were undertaken which demonstrated that rainfall-based design flood estimates in some regions of Australia using ARR2019 procedures tended to underestimate gauged flood frequency analysis estimates. As a result, Melbourne Water and DELWP commissioned a study to determine whether there was systematic bias in design flood estimates for Victorian catchments using the ARR2019 techniques and data sets.

A total of 25 catchments were identified across Victoria with calibrated flood event (RORB) models and a relatively reliable record of streamflow data. Within each catchment, the recorded streamflow data at each of the adopted gauge sites was used to derive at-site flood frequency curves for AEPs between 10% and 1%. These frequency analyses were used to compare the design flood estimates obtained using regional data from the ARR Data Hub.

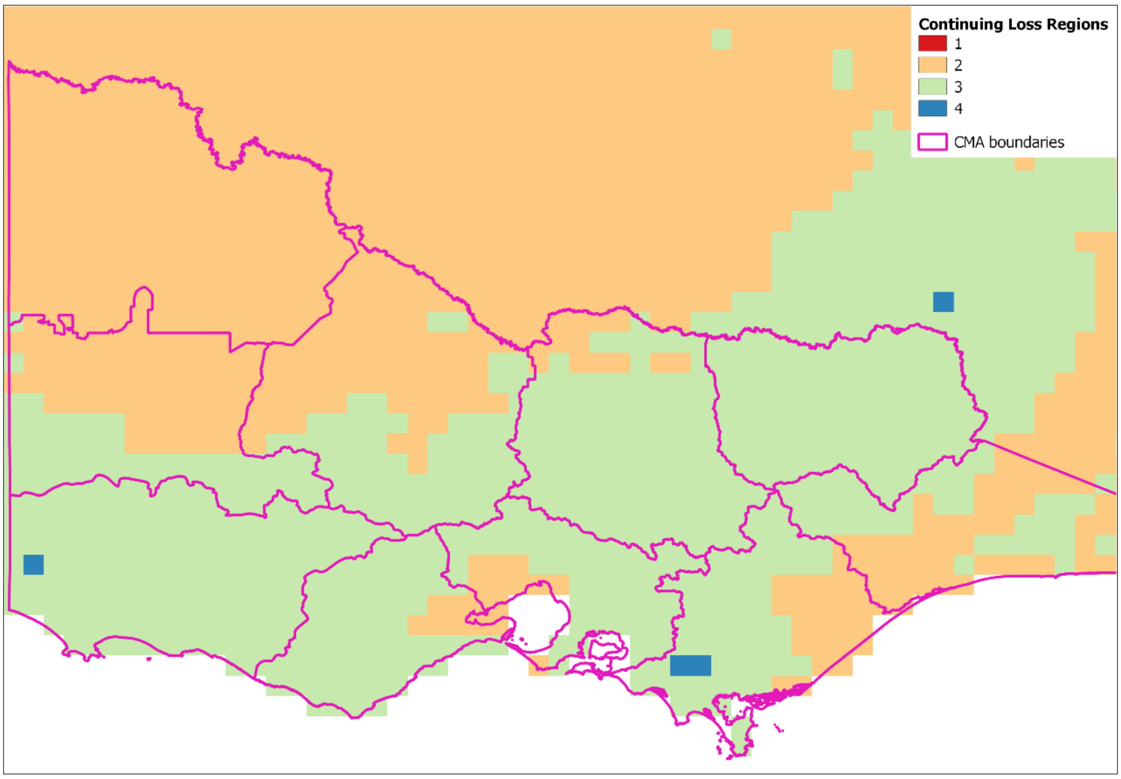
The outcome of this assessment indicated that the use of the standard ARR2019 design inputs for Victoria is likely to result in an underestimate of design flood peak flow in the majority of catchments. That is, if regional design information is relied upon without undertaking any local calibration then the resulting design flood estimates are likely to be lower than actual.

This project also tested the variability in flood estimates resulting from three different applications of pre-burst rainfall. The applications considered the adoption of:

- Pre-burst ratios from ARR2019 (holding the 1% AEP ratio constant for all rarer events) combined with pre-burst temporal patterns.
- Pre-burst depths from ARR2019 (holding the 1% AEP burst depth constant for all rarer events), applied as an adjustment to the initial loss value.
- Pre-burst ratios from Minty and Meighan (1999) and Jordan et al. (2005) combined with pre-burst temporal patterns.

The results indicated that up to the 1% AEP, the modelled peak flow quantiles were largely invariant to the pre-burst method adopted. Conceptually, use of a pre-burst ratio rather than absolute depth approach is preferred, particularly when the focus of the study is on AEPs rarer than 1%.

Preliminary investigations were trialled using three approaches to correct the bias observed in the design flood estimates for Victorian catchments. These investigations highlighted that there were regional differences in loss estimates corresponding to the four different hydroclimatic groupings (or "loss regions") used in ARR2019 to derive the underlying prediction equations. In particular, significant differences in loss values and benchmarking results were observed for those catchments which were close to or covered the boundary between loss regions. The spatial extent of the different loss regions used in ARR2019 for Victoria are shown in Figure ES-1.



■ **Figure ES-1: ARR loss regions for Victoria**

As the majority of catchments selected for this study were influenced by loss region 3, catchments within the influence of loss regions outside of region 3 were excluded from analysis. This resulted in recommendations only being applicable to catchments that lie within loss region 3.

On the basis of the investigations described in this report, it is recommended flood estimates obtained using ARR2019 Data Hub regional information should be derived using the 75th percentile pre-burst rainfall (in lieu of the median value) in combination with unmodified Data Hub values of initial and continuing loss. Given the distribution of catchments considered, this recommendation is only supported by information obtained for catchments within loss region 3.

In line with AR2019 recommendations (Section 3.3.3 of Book 5; Section 5 of Book 7), it is stressed that flood estimates are best derived using information local to the specific catchment of interest. A variety of approaches are available, and loss estimates can be obtained by one or more of the following approaches:

1. *Reconciliation with at-site flood frequency quantiles*: initial and continuing losses are varied within their expected range to achieve a reasonable level of agreement between estimates derived from rainfall-based modelling and flood frequency analysis.

2. *Reconciliation using within-catchment transposed flood quantiles:* streamflow observations are commonly available at gauging stations upstream or downstream of the site of interest, and

flood quantiles derived from these sites can be transposed to the site of interest and used for reconciliation as described in approach 1.

3. *Event-based calibration*: continuing losses obtained from calibration of historical events provide some indication of typical design values, noting that past historical events are biased towards wet catchment conditions; initial losses from historical events are highly variable and information from a small sample of events are of low utility (and therefore some form of reconciliation with other sources of information is recommended).

4. *Reconciliation using nearby catchment transposed flood quantiles:* regional flood quantiles derived using RFFE and other procedures (Section 3, Book 3, ARR2019) can be used for reconciliation as described in approach 1.

5. *Transposition of losses*: initial and continuing loss estimates validated on nearby catchments which are considered to be hydrologically similar.

6. *Regional losses (ARR Data Hub)*: unmodified initial and continuing loss estimates obtained from the Data Hub losses can be adopted in data poor areas, noting that in loss region 3 these should be combined with 75th percentile pre-burst values.

The above methods are listed in notional order of defensibility, where the first approach is the most preferred and the sixth method is the least preferred. However, for any given catchment the defensibility of the adopted approach varies with the relevance of the available data, where it is commonly necessary to make assumptions about how estimates might vary with catchment size, event severity, and the hydrologic similarity of catchment conditions. It is thus recommended that more than one approach be applied and that careful judgement be used to derive a single set of best estimates.

1. Introduction

The release of Australian Rainfall and Runoff (ARR) 2019 provided a range of new techniques and datasets to support design flood estimation in Australia. Whilst considerable effort was expended in developing the new guidance, there was limited opportunity for benchmarking the design floods estimated using these new datasets.

One example benchmarking study was completed by HARC in 2019, and considered 23 large rural catchments across Australia. This study demonstrated that rainfall-based design floods estimated using ARR2019 procedures and data tended to underestimate gauged flood frequency analysis. A more recent benchmarking study was completed by WMAwater (2018) focusing on NSW rural catchments. This study also demonstrated that there was an identifiable bias in design flood estimates for NSW catchments derived using ARR2019 procedures. These studies, coupled with other anecdotal evidence on benchmarking, led the Victorian Government to commission a benchmarking study to assess whether a similar bias existed for Victorian rural catchments.

This study was funded by Melbourne Water and DELWP and sponsored by the Victorian Floodplain Management Forum. The steering committee included representatives from Melbourne Water, the Department of Environment, Land, Water and Planning (DELWP) and other Victorian catchment management authorities (CMA). In late 2019, Melbourne Water engaged Associate Professor Rory Nathan (University of Melbourne), Tony Ladson (Moroka) and Peter Hill (HARC) to oversee technical delivery of the project. HARC were engaged to undertake the modelling and analysis associated with the project.

2. Project context

The release of ARR2019 provided a range of updated data sets and techniques for flood estimation. Whilst this has clearly been beneficial to industry, the guidance in ARR2019 has also raised a number of questions and inconsistencies which have not been fully dealt with or clarified within the document itself.

This section provides a brief overview of typical practice in flood estimation in Victoria, and also highlights a number of issues which warrant clarification or further investigation. This is not a thorough review of the entirety of ARR2019, rather a high-level overview of the current state of practice in Victoria to provide some context for undertaking this study.

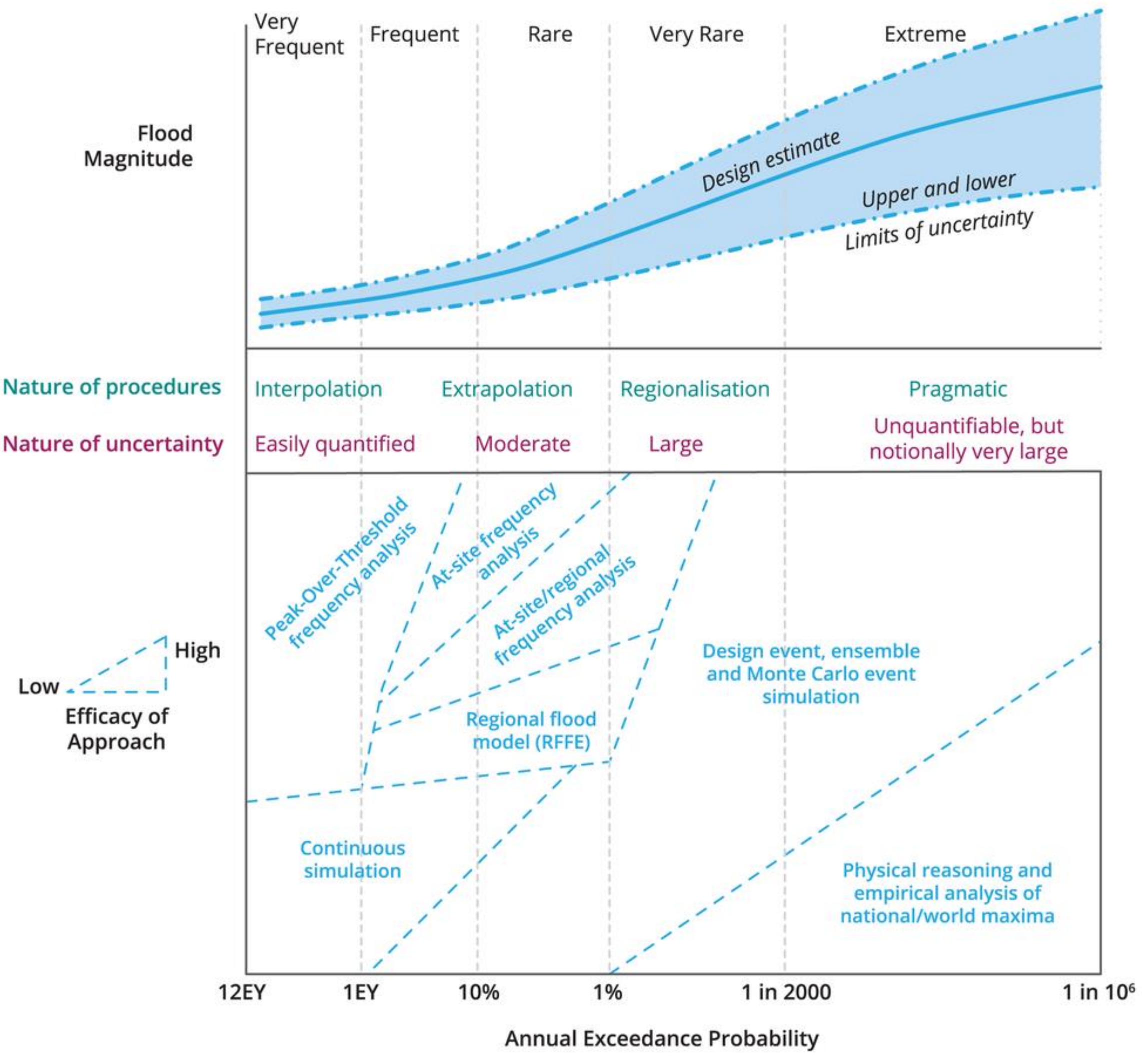
2.1 Design flood estimation procedures

The overall aim of the design flood estimation process is to define both the magnitude and probability of flood behaviour. Such flood estimates can be required to inform a wide range of engineering design, built environment and natural resource management activities, across a range of exceedance probabilities. ARR2019 provides a useful framework covering the types of procedures which can be used to estimate design floods for different probabilities of exceedance, as shown in Figure 2-1.

In general terms, much of the industry effort in flood estimation is focused on AEPs between the 10% and 0.05% AEP, with an overriding focus on the 1% AEP. In this range, ARR2019 recommends three main techniques for flood estimation:

- Where reliable gauged streamflow data exists and is still relevant to current catchment conditions, at-site (or regional) flood frequency analysis is the preferred method for design flood peak estimation for AEPs between 10% and 1%.
- In the absence of gauged data, the Regional Flood Frequency Estimation (RFFE) method may be appropriate. This technique provides peak flow only and is subject to a range of limitations on catchment area, land use and statistical uncertainty.
- The previous two approaches are typically unsuitable for many applications, and so rainfall-based approaches (ensemble or Monte Carlo simulation using a rainfall-runoff model) are used. ARR2019 provides a wealth of information, guidance and useful datasets for undertaking design flood estimation using rainfall-based techniques.

In rainfall-based estimates, design rainfall inputs are combined with catchment characteristics to produce flood estimates, through the use of a rainfall-runoff model. The procedure leverages the relatively reliable estimates of design rainfall depth and duration for a fixed probability of exceedance with the aim of producing floods of the same probability of exceedance. ARR2019 recommends using ensemble temporal pattern or joint probability (Monte Carlo) techniques to minimise the chance that there is a probability shift from input rainfall AEP to resulting flood AEP.



- **Figure 2-1: Illustration of relative efficacy of different approaches for the estimation of design floods**

ARR2019 has provided updated information on the following key inputs for rainfall-based flood estimation:

- Design rainfall intensity-frequency-duration data. These estimates were updated for all of Australia for all storm durations between 1 minute and 168 hours. Data is available for AEPs up to and including 0.05%.
- Rainfall areal reduction factors, to convert the point design rainfall depths described above into areal estimates that are applicable to a catchment.
- Pre-burst rainfall depths (discussed in more detail in Section 2.3)
- Rainfall temporal patterns. Sets of 10 temporal patterns are provided for a number of regions across Australia for each storm duration. The patterns are arranged in AEP and catchment area bins.

- Rainfall spatial patterns. ARR2019 recommends adoption of a fixed spatial pattern for each storm duration, typically derived from catchment scale variability in design rainfall depth.
- Regional initial and continuing loss values (discussed in more detail in Section 2.4).

Where reliable gauged streamflow data exists, the design flood estimates produced using rainfall-based techniques can be compared ('benchmarked') to peak flows derived from flood frequency analysis. This provides a means of establishing whether the combination of the ARR2019 inputs described above reproduces the gauged hydrologic behaviour of the catchment. Given the significant uncertainty and variability in flood behaviour (as well as the epistemic issues associated with data and model uncertainty), close match between the modelled and gauged design flood estimates is unlikely to occur in all cases. This project aims to determine whether the rainfall-based estimates tend to over or underestimate the gauged data in a systematic manner and explores options for addressing any such bias.

2.2 Using rainfall-runoff models

There is a range of conflicting information available within industry and the published literature on the design flood estimation process, specifically on the selection of model parameter values and reconciliation of model results with observed flood behaviour. The definition of terms such as model 'calibration' and 'verification', and the order in which these tasks are undertaken within the flood estimation process, vary.

2.2.1 Model calibration

Model calibration is the process of simulation of one or more historic flood events, typically the largest event(s) in the historic record for which reliable data is available. This requires information on recorded rainfalls for the selected historic events, including pluviograph data to define the rainfall temporal pattern. It also requires gauged streamflow hydrographs at one or more points within the catchment as a basis for comparison. Model calibration can be performed on the catchment of interest, or alternatively an adjacent or nearby catchment where it can be assumed that routing characteristics are similar and can be transposed to the catchment of interest.

During calibration, model parameter values are adjusted (within physically and regionally reasonable ranges) to achieve an optimal match between modelled and gauged hydrographs. However, the loss values derived from calibration to the largest recorded events are typically not suitable for use in design flood estimation.

Ideally, there should be consistency in model routing parameter and continuing loss values; both of which should be influenced by physical catchment characteristics.

The key outcome from calibration is selection of a routing parameter value for use in subsequent verification and design, typically selected as a weighted average from the parameter values from the individual events.

It should be noted that loss parameter values selected as part of model calibration should not be adopted for design, particularly initial loss. The individual events selected for calibration are typically the largest events in the gauged record, and are thus biased towards wetter than normal conditions. As such, an average of the loss values derived from calibration will tend to underestimate losses.

ARR Chapter 3 of ARR Book 5 (Hill and Thomson, 1999) notes that; "*The selection of high runoff events for loss derivation is likely to be biased towards wet antecedent conditions (ie. losses tend to be too low). Ideally, events should be selected on the basis of rainfall to remove this bias. …The main limitation of deriving losses directly from the analysis of recorded data is that they may not be compatible with the other design inputs and hence suitable for design flood estimation. That is, although the loss values may reflect the loss response observed for a number of events on the catchment, this does not guarantee that their application with other design inputs results in unbiased estimates of floods. For this reason, it is also desirable to reconcile design values with independent flood frequency estimates where possible*."

Where concurrent gauged streamflow and rainfall data is not available, model calibration cannot be completed. In these cases, an estimate of the routing parameter values can be made using regional information. Alternatively, routing parameter values can be estimated by comparison of hydrological modelling results with hydraulic (e.g. two-dimensional hydraulic models) and quasi-hydraulic models (e.g. kinematic routing models or the deterministic rational method). The routing parameter values within the hydrological model, are altered to match the routing characteristics from the hydraulic model.

2.2.2 Model verification in gauged catchments

Model verification is the selection/confirmation of model parameter values on the basis that the rainfall-based flood estimates are consistent with the frequency analysis of recorded streamflow. The focus AEPs will depend upon the application but typically is in the range of 10% and 1% AEP. Design inputs are adopted and the model run in ensemble or Monte Carlo mode. A gauged at-site or regional flood frequency analysis is required as a basis for comparison. Verification can be performed on the catchment of interest or an adjacent or nearby catchment where it can be assumed loss characteristics are similar and can be transposed to the catchment of interest.

For verification, the model routing parameter values should be held constant at the value selected for design. Model loss parameter values are adjusted (within physically and regionally reasonable ranges) to achieve an optimal match between the modelled rainfall-based flood estimates and an at-site or regional flood frequency curve. Ideally there would be some consistency evident in the average continuing loss values derived from calibration to gauged historic events (where this is possible) and the value adopted for verification.

Ideally, the loss estimates used for verification should not vary by AEP, unless there are strong reasons for doing so. ARR Project 6 which underpinned the guidance in ARR relating to losses could not identify any evidence that loss values varied systematically with event severity and there is limited physical justification for adjusting loss values by AEP.

2.2.3 Loss estimation in ungagged catchments

In ungauged catchments, a regional flood frequency curve can be derived using the RFFE tool for catchments with less than 10% imperviousness, sized between 0.5 and 1,000 km^2 and without major storages or dams. Where the catchment of interest has significant imperviousness or upstream dams, it may be possible to develop a 'naturalised' model which can be used to set pervious loss values in comparison to RFFE.

Alternatively, or in conjunction with RFFE, the ARR2019 regional loss estimates can be used for ungauged catchments. The applicability of these loss estimates in conjunction with other design inputs such as pre-burst rainfall is the key focus of this investigation.

2.2.4 Design flood simulation

Having completed model calibration (or selected routing parameter values from regional estimates) and model verification (or reconciliation of regional loss estimates with regional flood frequency estimates), the model and its inputs can be used to derive design flood estimates.

2.3 Pre-burst rainfall

Prior to the release of ARR2019, pre-burst rainfall (and the concept of complete storms rather than design bursts) was typically only considered in detailed extreme flood hydrology studies.

Design pre-burst rainfall data for long duration storms was analysed as part of the development of the Bureau of Meteorology's Generalised Southeast Australia Method (GSAM) PMP (Minty & Meighen, 1999). This dataset provided a single pre-burst temporal pattern for durations of 12, 24, 36, 48, 72, 96 and 120 hours for coastal and inland regions. The temporal pattern was expressed as a ratio to the burst depth, thus allowing the pre-burst depth to scale with AEP.

Other research provided pre-burst estimates for short duration storms (Jordan et al., 2005). A single pre-burst temporal pattern was provided for all short duration events, between 0.5 hours to 12 hours, which was expressed as a ratio to the burst depth.

Pre-burst rainfall depths were estimated as part of ARR2019 revision project 3 (WMAwater, 2015). The data is provided as both absolute depths and ratios of the design burst, for a range of exceedance percentiles for durations between 1 and 72 hours and AEPs between 50% and 1%. The data is provided (via the ARR Data Hub) on a gridded basis, and thus varies from catchment to catchment. Pre-burst rainfall is useful as it allows fixed losses to be used over the whole probability domain unlike other methods such as burst losses which need to be varied. A detailed review of the ARR2019 pre-burst data is included as Appendix A . No pre-burst rainfall temporal patterns are provided in ARR2019, and there is limited advice as to how pre-burst rainfall should be accounted for in hydrologic model verification and design flood estimates. In general, there are two main methods used by industry to simulate the effects of pre-burst:

- A pre-burst temporal pattern is prepended to the design burst temporal pattern. The actual pre-burst rainfall depth is then applied using the ratio data from the ARR Data Hub. This is the approach used in RORBwin.
- The estimated pre-burst rainfall depth from the ARR Data Hub is subtracted from the complete storm initial loss and the design burst only is simulated. Where the pre-burst depth is larger than the initial loss, the residual pre-burst is either ignored or added to the first timestep of the design burst. This is the approach used in Storm Injector, XP-Rafts and URBS.

2.4 Regional loss estimates

Regional estimates of median complete storm initial loss and continuing loss for rural catchments were derived as part of the ARR2019 revision (Hill et al, 2014 and 2015)

For 38 catchments across Australia, loss parameter values were derived for a large number of historic events through the analysis of recorded rainfall and streamflow. The catchments were all less than 100 km² to reduce the influence of flood routing.

It should be noted that this work was undertaken on complete storms, and considerable effort was expended to derive local storm samples for each catchment. This work was undertaken in parallel to the pre-burst analysis described in the previous section, and the two studies used different definitions of a complete storm. As such, it has long been recognised that there is a potential mis-match between the regional complete storm initial loss values and the pre-burst values (Scorah et al, 2015).

Having estimated losses at a limited number of sites across Australia, the results needed to be regionalised so that gridded data sets covering the whole of Australia were made available through the ARR Data Hub.

These loss estimates were derived by developing prediction equations for four hydrologically similar regions across Australia. The prediction equations used a range of independent variables, many of which were drawn from analysis of the Australian Water Resource Assessment – Landscape (AWRA-L) model (Frost et al, 2015). Selection of the independent variables and fitting of the prediction equations was undertaken using a linear regression analysis on loss values fitted in 35 catchments across Australia (Hill et al, 2016).

2.5 Treatment of variability

ARR2019 describes two board types of uncertainty:

- *Aleatory* -refers to uncertainty that arises through natural randomness or natural variability that we observe in nature.
- *Epistemic*- refers to uncertainty that is associated with the state of knowledge of a physical system, our ability to measure it and the inaccuracies in our predictions of the physical system.

ARR2019 formally introduced treatment of aleatory uncertainty in rainfall temporal pattern (and other flood generating factors) into flood estimation guidance. The document offers two main approaches to treatment of variability: ensemble simulation of temporal pattern variability and joint probability (Monte Carlo) simulation of one or more variables.

There are numerous technical reviews of the benefits associated with ensemble and Monte Carlo simulations over traditional deterministic methods, with the paper by Nathan et al (2016) serving as a comprehensive summary of the topic. For clarity and simplicity, all of the simulations undertaken for this study used a Monte Carlo joint probability framework implemented in the publicly available version of RORBwin. This is described in more detail in Section 3.

One area where ARR2019 provides little guidance and there is limited research, is the translation of treatment of variability from hydrologic (i.e. with a focus on peak flow estimation) to hydraulic (i.e. with a focus on peak flood depth) modelling. The level of complexity here is confounded by a number of issues, including the relative run time of complex 2D hydraulic models relative to hydrologic models, as well as significant non-linearity in the conversion from peak flow to peak water level. Furthermore, whilst most hydrologic studies focus primarily on peak flow, hydrograph volume can be a just as or more important driver of peak flood depth particularly in lowland regions.

There appear to be a couple of main ways in which this issue is currently handled across industry:

- Selection of a 'representative' hydrograph from the suite of ensemble or Monte Carlo results for each AEP and possibly for a number of durations. This approach minimises hydraulic model runs but requires an assumption that probability neutrality is preserved across the hydrologic/hydraulic model interface.
- Incorporation of the treatment of variability into the hydraulic model. This is typically done by running a large number of ensemble members in the hydraulic model and then mapping median water levels on a regional or grid cell basis. This approach can be onerous in terms of the number of runs required for the hydraulic analysis.

Whilst these approaches are relatively straightforward when considering design estimates at a point, they both become highly complex when mapping floods across a region, as is commonly done in a number of studies. This requires that changes in storm duration and areal reduction factors are accounted for as upstream catchment area increases, and can result in the number of hydraulic model runs increasing numerous times over.

The paper by Scorah et al (2018) benchmarks several of these alternatives, however it is clear that additional research and investigation is needed here. It should be noted that this project focuses on the hydrologic aspects and hence does not explore these issues associated with the hydraulic modelling.

2.6 Climate Adaptation

ARR2019 Book 1 highlights that design flood estimates are likely to be impacted by climate change. Although ARR acknowledges that antecedent conditions, such as initial loss, could change under climate change, there is currently no industry guidance on how best to account for this. There is also limited information available on the likely impact of climate change on rare and extreme rainfalls. As an interim approach for practitioners until further research is undertaken, ARR recommends the use of projections developed as part of the Global Climate Models by CSRIO. The models provide an adjustment factor which is applied to rainfall depths based on different greenhouse gas and aerosol concentrations and projected time periods.

Although this project provides no additional guidance around climate change projections, its intent is to provide a firmer base for estimating design floods in Victoria. This enables an improved basis for adjusting to climate change once further research on this subject is completed. By improving current day design flood estimates, it also enables flood risk to be better defined therefore placing practitioners in a better position to meet the challenges of climate change and climate variability.

2.7 Summary

The key question which drove this benchmarking project was whether, on a statistical basis, the combination of the design inputs provided by ARR2019 produces unbiased estimates of design floods for Victorian catchments.

At a conceptual level, it is noted that the definition of a storm used in the derivation of the regional loss estimates differed from that used to define the pre-burst rainfall design inputs. As such, it is conceptually possible that the combination of these two inputs may be one underlying contributor to a systemic bias.

Published data, unpublished analysis and anecdotal evidence suggests that there is a bias, but this has (to date) not been formally established in Victoria. The study further investigates, at a high level, what could be done to treat or account for this bias.

2.8 Adopted approach

At a high level, the approach taken was to identify a series of catchments in Victoria with a reliable gauged streamflow data set. This data was used to estimate design flood quantiles via at-site flood frequency analysis. Hydrologic models were then established for these catchments, and run using the design inputs from ARR2019. Comparison of the modelled and gauged flood frequency estimates was used to determine if a bias existed. The study focused primarily on pre-burst rainfall and regional loss estimates.

3. Data collation and catchment selection

3.1 Selection Criteria

To identify rural catchments for use in this study, a number of factors were considered. These included:

- The range of climatic, topographic and land use zones across Victoria
- A range of catchments of different sizes, with limited high-density urban area
- The number of catchments and streamflow gauges which could successfully be analysed given the resources available for the project
- Streamflow gauges with long and relatively stationary periods of record (i.e. not impacted by upstream storages or significant changes in urbanisation)
- Streamflow gauges with well-established rating curves gauged to a reasonable proportion of the flood of record. The suitability was established by reviewing factors such as the rating ratio (i.e. the ratio of the largest recorded flow to the largest gauged flow)
- Catchments with established, calibrated RORB models
- Existing calibrated RORB models from flood studies

RORB was selected as the general runoff and streamflow routing program used to undertake this analysis due to its functionality. It subtracts losses from rainfall to determine rainfall excess and routes this through catchment storages to produce streamflow hydrographs at points of interest. The model is spatially distributed, non-linear, and applicable to both rural and urban catchments. It makes provision for both temporal and areal distribution of rainfall as well as losses, and can model flows at any number of points throughout a catchment (including upstream and downstream of reservoirs). RORB also has the capacity to use a Monte-Carlo approach to produce design flood estimates that incorporate the joint probability of several factors that influence flood characteristics. RORB also enables the prepend of pre-burst rainfall to design bursts either through allowing the user definition or adopting the Minty and Meighen (1999) approach for durations greater than 12 hours.

3.2 Catchment selection

An initial analysis identified a number of suitable catchments which had existing calibrated RORB models. These included:

- ARR Revision Project 6 catchments within Victoria (Hill et al, 2016).
- CRC Testing of Improved Inputs for Design Flood Estimation in South-Eastern Australia (Hill et al. 1996)
- An internal HARC benchmarking study on ARR loss estimation.

The list of potential catchments was refined through analysis of the selection criteria outlined above. These preliminary catchments were then presented at the February flood forum where Melbourne Water and the CMA's were able to provide input. This resulted in further refinement of catchments and inclusion of additional CMA catchments which had existing calibrated RORB models and met the required criteria. It was also identified that there were no catchments within Melbfourne Water area because there were no existing calibrated RORB models with limited urban area which met the selection criteria. As a result, RORB models at Lerderderg River at Sardine Creek Obrien Crossing and Riddells Creek at Riddells Creek were created and calibrated in order to be used for this assessment. The creation and calibration of the RORB models is described in Appendix B.

It was also highlighted that there were no suitable catchments within the Mallee and Wimmera CMA regions. However, due to the lack of catchments which met the outlined criteria it was considered reasonable that the north western region of Victoria was not included.

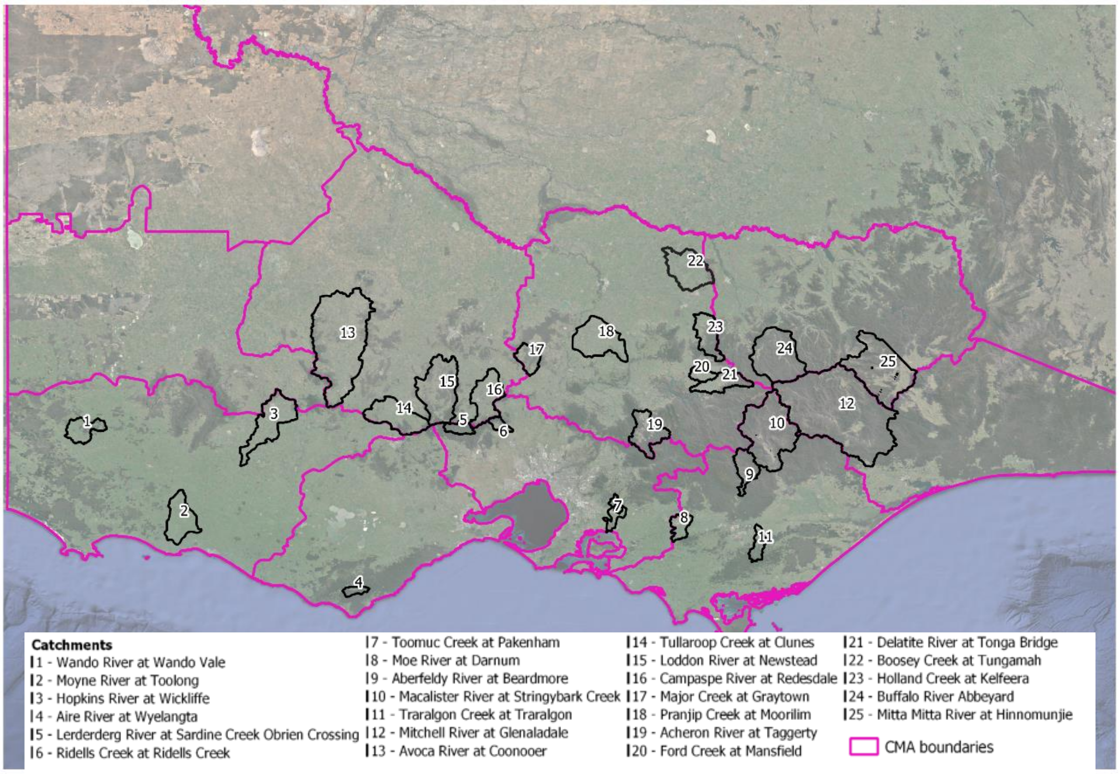
A total of 25 catchments were ultimately adopted to undertake this benchmarking assessment. Table 3-1 outlines the adopted gauge site and key characteristics for these catchments and Figure 3-1 outlines the location and size of each of the selected catchments. One of the characteristics provided is the rating ratio, which is the largest recorded flow point divided by the maximum measured (gauged) flow for the station and hence is a measure of the degree to which the rating curve has been extrapolated beyond the measured values (Haddad et al, 2010). Based on research undertaken by Haddad et al (2010), an average rating ratio of 4 was deemed acceptable. Key characteristics of the catchments are highlighted in Figure 3-2 and Figure 3-3.

Table 3-2 and Figure 3-3 summarises the key parameters of the adopted RORB models for each of the catchments. These parameters include k_c, the principal routing parameter in RORB and c which is the ratio between k_c and d_{av} which represents the characteristic runoff response of the catchment that is independent of catchment size. The parameter d_{av} is the area-weighted average length of flow path from the sub-area centroid to the catchment outlet.

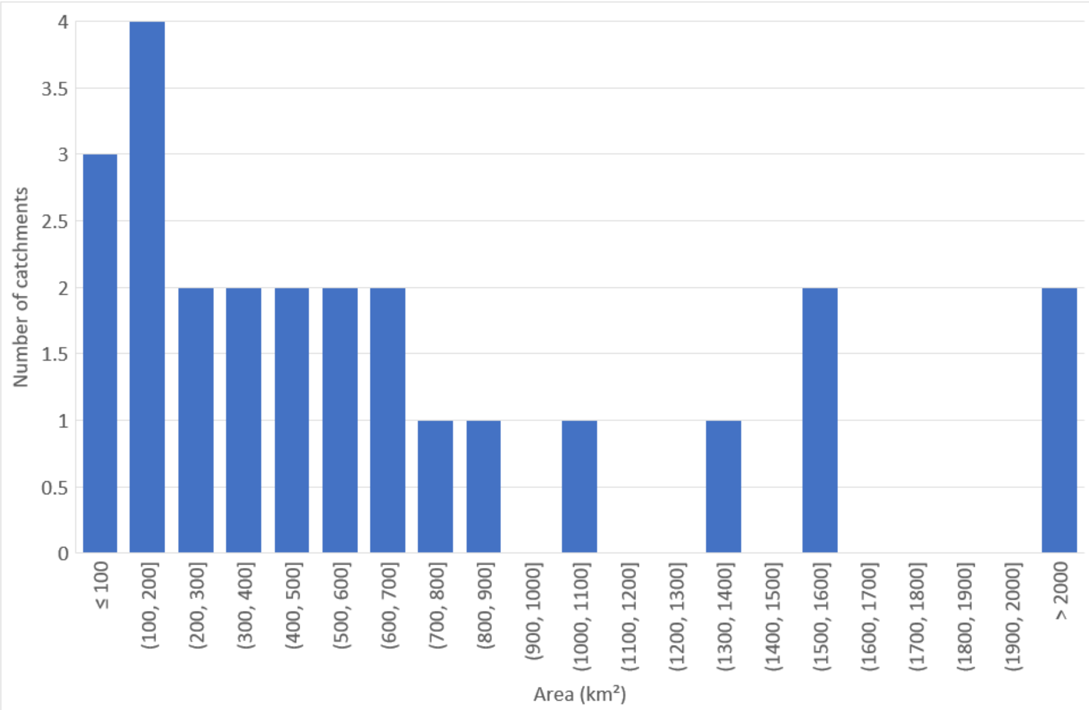
From an analysis of 39 catchments from around Victoria, Pearse et al (2002) found that the median value of c was approximately 1.25 with a range of between 0.75 to 2.07 and the analysis of other data sets gave median values of 0.96 and 1.14. Thus, the c values for the benchmarking catchments are broadly within the expected range. However, the variation in c reinforces the importance of calibrating the routing parameters when there is sufficient at-site data.

Table 3-1: Adopted catchments for benchmarking

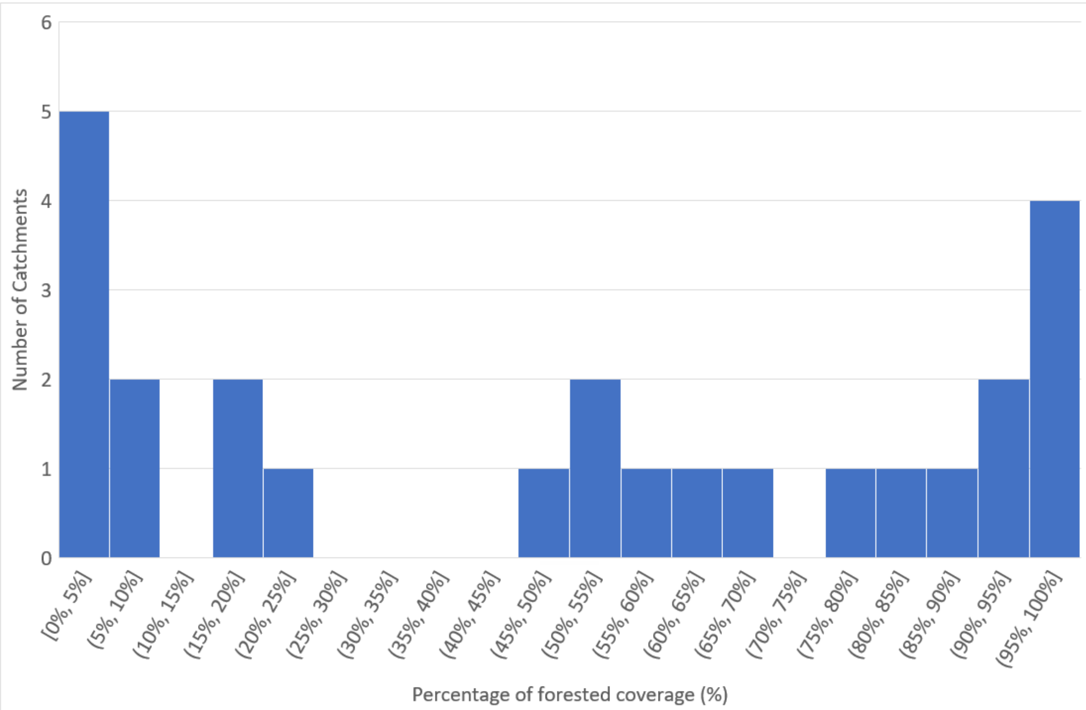
	Gauge name	Gauge number	CMA region	Catchment Area (km^2)	Rating Ratio	Forested area (%)	Mean annual rainfall (mm)
1	Wando River at Wando Vale	238223	Glenelg Hopkins	168	1.11	4	703
2	Moyne River at Toolong	237200	Glenelg Hopkins	570	1.02	0	693
3	Hopkins River at Wickliffe	236202	Glenelg Hopkins	1,350	1.85	4	536
4	Aire River at Wyelangta	235219	Corangamite	90	8.50	81	1,620
5	Lerderderg River at Sardine Creek Obrien Crossing	231213	Melbourne Water	153	2.04	95	910
6	Riddells Creek at Riddells Creek	230204	Melbourne Water	79	1.10	67	725
7	Toomuc Creek at Pakenham	228217	Melbourne Water	42	2.30	10	819
8	Moe River at Darnum	226209	West Gippsland	214	1.74	92	850
9	Aberfeldy River at Beardmore	225213	West Gippsland	347	2.87	100	1,100
10	Macalister River at Stringybark Creek	225221	West Gippsland	1,540	5.12	95	953
11	Traralgon Creek at Traralgon	226023	West Gippsland	189	3.12	61	935
12	Mitchell River at Glenaladale	224203	East Gippsland	3,900	2.06	94	1,060
13	Avoca River at Coonooer	408200	North Central	2,670	3.18	24	505
14	Tullaroop Creek at Clunes	407222	North Central	632	2.41	16	615
15	Loddon River at Newstead	407215	North Central	1,090	2.97	51	565
16	Campaspe River at Redesdale	406213	North Central	629	1.09	19	785
17	Major Creek at Graytown	405248	Goulburn Broken	291	5.05	52	575
18	Pranjip Creek at Moorilim	405226	Goulburn Broken	822	1.95	4	608
19	Acheron River at Taggerty	405209	Goulburn Broken	545	2.85	86	1,230
20	Ford Creek at Mansfield	405245	Goulburn Broken	117	5.72	2	833
21	Delatite River at Tonga Bridge	405214	Goulburn Broken	368	2.96	94	967
22	Boosey Creek at Tungamah	404204	Goulburn Broken	739	2.43	9	521
23	Holland Creek at Kelfeera	404207	Goulburn Broken	450	1.91	60	1,040
24	Buffalo River at Abbeyard	403222	North East	425	2.57	96	1,330
25	Mitta Mitta River at Hinnomunjie	401203	North East	1,530	1.29	77	919



■ **Figure 3-1: Selected Catchments for ARR2019 benchmarking**



■ **Figure 3-2: Distribution of the selected catchment areas**



■ **Figure 3-3: Distribution of the selected catchment forest coverage**

Table 3-2: RORB model parameters for the catchments

	Gauge name	k_c	c (k_c/d_{av})
1	Wando River at Wando Vale	16.2	0.8
2	Moyne River at Toolong	46	1.5
3	Hopkins River at Wickliffe	120	2.7
4	Aire River at Wyelangta	18.5	1.7
5	Lerderderg River at Sardine Creek Obrien Crossing	13	1.2
6	Riddells Creek at Riddells Creek	14	1.1
7	Toomuc Creek at Pakenham	12	0.8
8	Moe River at Darnum	29.1	3.0
9	Aberfeldy River at Beardmore	36	1.4
10	Macalister River at Stringybark Creek	62	1.0
11	Traralgon Creek at Traralgon	10	1.2
12	Mitchell River at Glenaladale	76.5	0.7
13	Avoca River at Coonooer	40.6	1.1
14	Tullaroop Creek at Clunes	23	0.9
15	Loddon River at Newstead	29	1.0
16	Campaspe River at Redesdale	35	0.7
17	Major Creek at Graytown	22	1.1
18	Pranjip Creek at Moorilim	78	2.2
19	Acheron River at Taggerty	38.5	1.3
20	Ford Creek at Mansfield	5.5	0.5
21	Delatite River at Tonga Bridge	27	1.1
22	Boosey Creek at Tungamah	110	3.0
23	Holland Creek at Kelfeera	23	0.8
24	Buffalo River at Abbeyard	40	2.5
25	Mitta Mitta River at Hinnomunjie	65	1.8

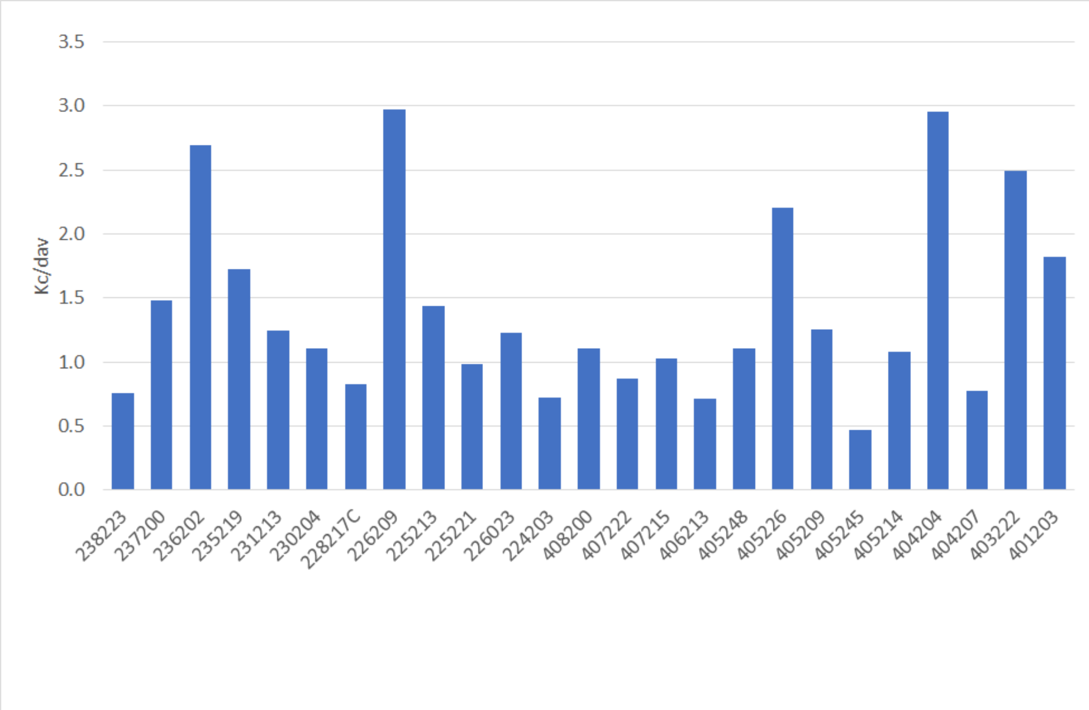


Figure 3-4: The RORB model c values (k_c/d_{av}) for the selected catchments

4. At-site flood frequency analysis

The recorded streamflow data at each of the adopted gauge sites was analysed to estimate flood frequency analysis. The process used to extract annual maxima and fit probability distributions is described in this section.

4.1 Baseflow analysis and extraction

Streamflow gauges record total flow, comprised of surface runoff (or quickflow) and baseflow. By contrast, the design flood estimation techniques outlined in ARR2019 focus primarily on surface runoff; baseflow is typically only estimated where it is a significant proportion of the total flow, or the focus of the study is on simulation of total flood volume.

The possible influence of baseflow is an important consideration of the design flood estimation process. Firstly, a determination needs to be made about whether baseflow is significant in comparison to total peak flow for the catchment(s) of interest. Where it is considered to be significant, baseflow then needs to be treated as part of the model calibration phase, the model verification phase (where these are both relevant) as well as the design flood simulation phase, using a range of possible techniques.

Assessment of the significance of baseflow for the gauged catchments considered as part of this study was undertaken by firstly separating baseflow from recorded total flow. The method adopted to do this was a digital filter applied to daily maximum recorded total flow data. This approach uses the Lyne and Hollick filter (Ladson et al., 2013) as referenced in Chapter 4, Book 5 of ARR2019 (Hill et al., 2019). Three passes were used with the digital filter and a filter parameter (α) of 0.925.

Having separated baseflow from total flow in this manner, annual maxima were then extracted from the total flow timeseries. The baseflow value on the corresponding day of each annual maximum was also extracted. In flood estimation, it is typically the baseflow corresponding to the peak surface runoff that is of interest, however given that baseflows were a relatively small contributor to the peak (refer to discussion below) the daily value was used rather than analyse the data at a finer resolution. These values were then compared to determine the percentage contribution of baseflow to each annual maximum. The average baseflow contribution as a percentage of total flow was then calculated for all annual maxima at each gauge site as well as the largest five annual maxima at each gauge site. This is shown in Table 4-1.

It can be seen that average baseflow contribution varies significantly across the gauge sites and with flood magnitude. As could be expected, the contribution is markedly lower for the largest five annual maxima, which are the values that tend to drive the shape of the fitted flood frequency curve. For these largest five annual maxima, only the total flow data at 6 sites suggested a baseflow contribution larger than 5%. Furthermore, of these 6 sites the maximum baseflow contribution was approximately 7%.

Table 4-1: Summary of average baseflow contribution to annual maxima

	Gauge name	Average baseflow contribution – all annual maxima (%)	Average baseflow contribution – largest five annual maxima (%)
1	Wando River at Wando Vale	7.4	1.7
2	Moyne River at Toolong	9.7	5.1
3	Hopkins River at Wickliffe	12.5	2.6
4	Aire River at Wyelangta	9.1	1.2
5	Lerderderg River at Sardine Creek Obrien Crossing	3.8	1.1
6	Riddells Creek at Riddells Creek	5.5	1.0
7	Toomuc Creek at Pakenham	3.8	1.0
8	Moe River at Darnum	8.6	4.6
9	Aberfeldy River at Beardmore	6.5	0.8
10	Macalister River at Stringybark Creek	10.1	2.8
11	Traralgon Creek at Traralgon	10.7	1.0
12	Mitchell River at Glenaladale	12.3	2.3
13	Avoca River at Coonooer	7.3	1.8
14	Tullaroop Creek at Clunes	7.3	1.8
15	Loddon River at Newstead	6.6	1.4
16	Campaspe River at Redesdale	6.9	1.9
17	Major Creek at Graytown	3.6	1.3
18	Pranjip Creek at Moorilim	10.2	5.8
19	Acheron River at Taggerty	23.1	7.7
20	Ford Creek at Mansfield	1.7	0.6
21	Delatite River at Tonga Bridge	8.7	3.8
22	Boosey Creek at Tungamah	15.8	6.8
23	Holland Creek at Kelfeera	7.4	1.9
24	Buffalo River at Abbeyard	13.8	6.7
25	Mitta Mitta River at Hinnomunjie	24.7	7.3

Having assessed the significance of baseflow to the largest annual maxima at the adopted gauge sites, it was concluded that baseflow is overall a non-negligible but relatively minor contributor to the annual maxima of interest. As such, there was a need to account for this baseflow contribution when comparing the regime of recorded flood behaviour at the gauge sites to rainfall-based flood quantiles derived from model simulations. Two main methods for accounting for baseflow were considered:

- Remove baseflow from the recorded total flow at the gauge sites to derive a surface runoff only timeseries. Annual maxima extracted from this surface runoff timeseries can then be used to produce at-site flood frequency analyses which can be directly compared to rainfall-based flood quantiles.
- Extract annual maxima from the recorded total flow timeseries records at each gauge site. The resulting at-site flood frequency analyses would then be comprised of both surface runoff and baseflow. Design baseflow estimates could then be produced for each gauged catchment and

added to the rainfall-based flood quantiles prior to comparing them to the total flow flood frequency analyses.

For this project, it was decided to adopt the first approach, on the basis that development of design baseflow estimates would introduce additional epistemic uncertainty to the modelling process. Assumptions and simplifications would need to be made to represent the temporal behaviour of baseflow throughout the design events as well as how the magnitude of baseflow varies by AEP. For this project, the focus of the model verification was on surface runoff peak flow only, and so additional uncertainty was eliminated by removing the need to derive design baseflow estimates. The adopted approach may not be suitable in cases where total flood volume is of importance.

4.2 Annual maxima

Annual maxima were extracted from the daily maximum surface runoff (quickflow) timeseries for each gauge, which was computed using the techniques described in Section 4.1.

Seasonality of the largest floods at each gauge was investigated in order to determine the appropriate 12-month period over which to extract the maxima. A sub-set of three gauges was selected from the list of adopted gauge sites to broadly capture different climatic, topographic and catchment conditions across Victoria. The three selected gauges were Wando River at Wando Vale, Boosey Creek at Tungamah and Mitta Mitta River at Hinnomunjie. For these gauges, all independent flood peaks over a defined flow threshold were extracted from gauged daily maximum total flow record. The threshold value was set such that the total number of peaks extracted was approximately equal to the number of years of record. Flood peaks were considered to be independent if:

- They were more than 7 days apart, and
- The daily flow receded to less than 75% of the peak flow between the two peaks

The date of peak selected from the records in this manner was then collated and a histogram was then constructed to show seasonal variability, as summarised in Figure 4-1.

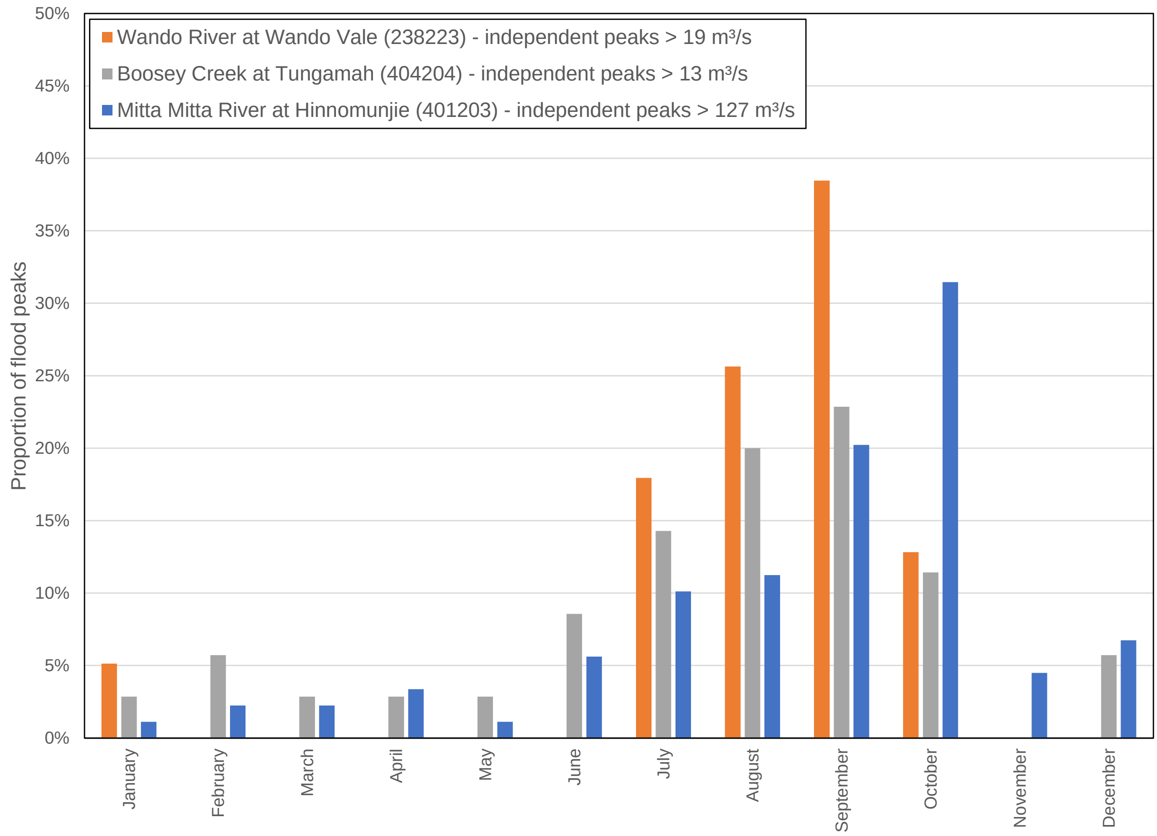


Figure 4-1: Seasonality of flood peaks for three gauges

This analysis demonstrated that seasonality for the representative three gauges is strongly weighted towards the late winter/spring seasons. This variation is relatively consistent across all three sites, suggesting that flood seasonality is not significantly impacted by factors such as topography or location within the state (excluding the Mallee and Wimmera regions which were not included as part of this investigation). Whilst it is acknowledged that there have been a number of significant summer flood events (most recently the large floods which occurred between December 2010 and January 2011), the vast majority of recorded flood activity occurs in spring. As such, it was concluded that defining the annual period as running from 1 January to 31 December would be most appropriate.

Extraction of the annual maxima also necessarily considered periods of missing data. In general, if more than 30% of the daily maximum data in any given year was flagged as missing, and the annual maxima from that year was outside the July to October range, the year was excluded from further analysis. A summary of the total number of years of record at each gauge and the number of included annual maxima is shown as Table 4-2. The period of record for each gauge is shown in Figure 4-2 and demonstrates that the records span similar periods and therefore represent similar mixes of wet and dry periods resulting from climate drivers such as the Interdecadal Pacific Oscillation (IPO).

The largest 10 extracted annual maxima and their corresponding dates for all gauges are tabulated in Appendix C.

Table 4-2: Summary of missing data for adopted gauge sites

	Gauge name	Total number of years of record[1]	Number of annual maxima[2]
1	Wando River at Wando Vale	47	45
2	Moyne River at Toolong	47	46
3	Hopkins River at Wickliffe	57	54
4	Aire River at Wyelangta	47	44
5	Lerderderg River at Sardine Creek Obrien Crossing	61	60
6	Riddells Creek at Riddells Creek	84	80
7	Toomuc Creek at Pakenham	44	42
8	Moe River at Darnum	72	70
9	Aberfeldy River at Beardmore	51	56
10	Macalister River at Stringybark Creek	57	51
11	Traralgon Creek at Traralgon	53	54
12	Mitchell River at Glenaladale	84	79
13	Avoca River at Coonooer	57	52
14	Tullaroop Creek at Clunes	41	40
15	Loddon River at Newstead	48	37
16	Campaspe River at Redesdale	46	45
17	Major Creek at Graytown	50	40
18	Pranjip Creek at Moorilim	47	45
19	Acheron River at Taggerty	48	46
20	Ford Creek at Mansfield	51	50
21	Delatite River at Tonga Bridge	64	63
22	Boosey Creek at Tungamah	39	36
23	Holland Creek at Kelfeera	61	60
24	Buffalo River at Abbeyard	56	55
25	Mitta Mitta River at Hinnomunjie	70	68

[1] Includes any year in the data record where there are observations

[2] Excludes annual maxima from years which were considered suspect due to lack of data for complete year and where timing of the annual maxima did not correlate with rainfall records

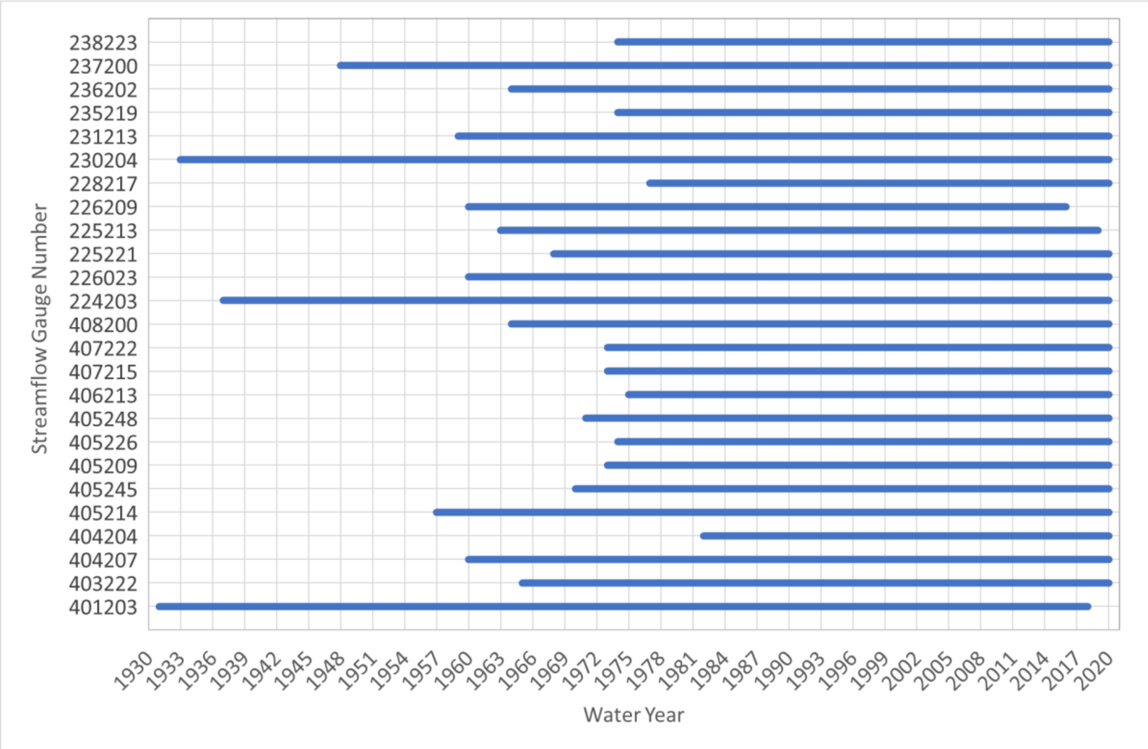


Figure 4-2: Streamflow records available for benchmarking catchments

4.3 Flood frequency analysis

Probability distributions were fitted to the extracted annual maxima to derive gauged at-site flood frequency analyses for each gauge site. Chapter 2 of Book 3 of ARR2019 (Kuczera & Franks, 2019) allows a range of probability models to be used. Two approaches recommended in ARR2019 for selection and fitting of probability distributions are:

- Generalised Extreme Value (GEV) distribution fitted using LH-moments
- Log Pearson III (LPIII) distribution fitted using a Bayesian approach

Consideration was given to both the GEV and LPIII approaches in order to select the technique which provided the best fits in general for a selected sub-set of gauges, with the assumption that these conclusions could be extrapolated to the remaining gauges. The three gauges selected for testing were the Mitta Mitta River, Boosey Creek and Wando River. Both LPIII and GEV distributions are widely adopted for flood frequency analysis in Australia, and in general any differences in best estimates derived using these methods are small compared to the width of the associated confidence limits.

Note that the probability distributions were fitted to the annual maxima extracted from the gauged surface runoff (quickflow) timeseries at each gauge location only. Consideration was given to including estimates of significant pre-gauge floods; however, none were identified for the adopted gauge sites.

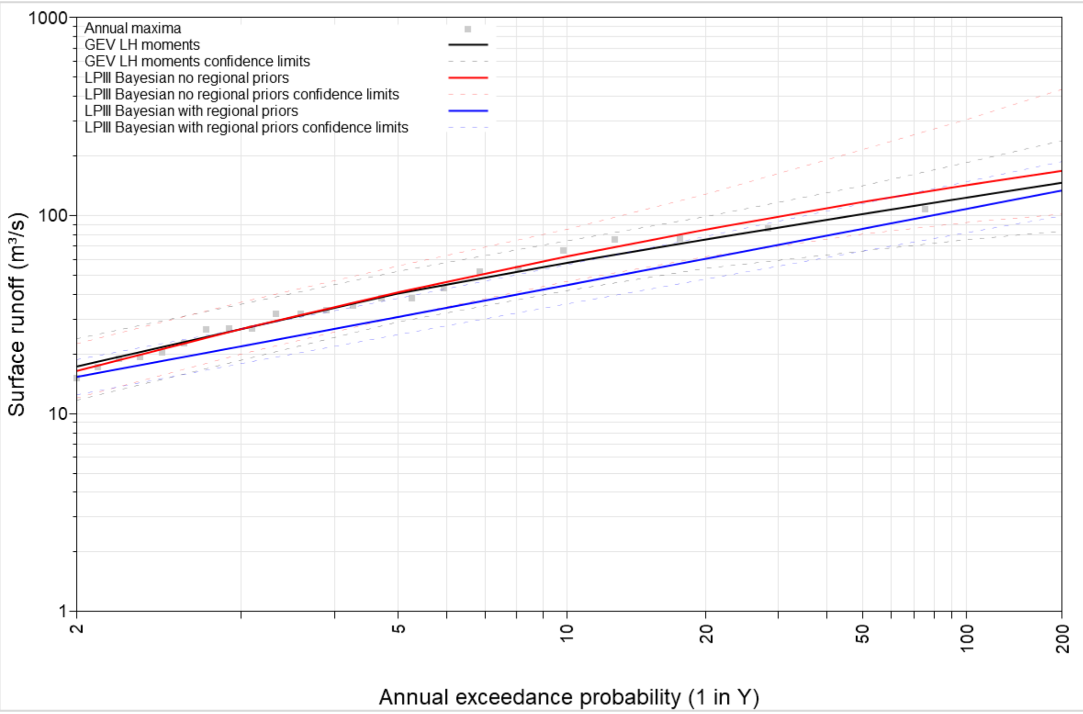
4.3.1 Distribution and fitting technique

The GEV distribution was fitted to the gauged surface runoff annual maxima using LH-moments (Wang, 1997). The 95% confidence intervals were estimated using 500 Monte Carlo samples from the fitted distribution using a parametric bootstrap procedure. An LH shift of two was adopted with no low flow threshold, based on the advice in published literature (Hosking & Wallis, 1997).

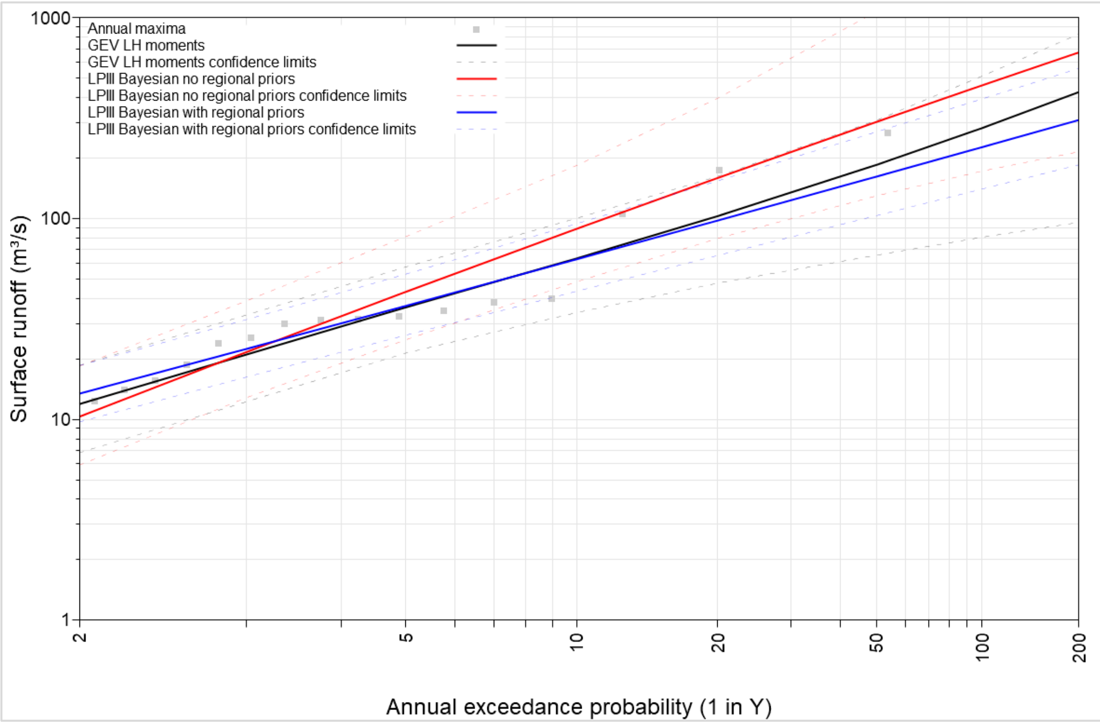
The LPIII distribution was fitted to the gauged surface runoff annual maxima using the Bayesian fitting technique implemented in the software program TUFLOW FLIKE version 5.0.251.0. A multiple Grubbs-Beck test was applied to censor low flow outliers. This process was repeated twice; using only the gauged annual maxima and using gauged annual maxima supplemented by regional prior distribution information derived from the Regional Flood Frequency Estimation (RFFE) tool (Rahman et al., 2019).

Comparison plots showing the fitted GEV and LPIII distributions for the selected sub-set of gauge sites are included as Figure 4-3, Figure 4-4 and Figure 4-5. Annual maxima are shown on these plots using a Cunnane plotting position with an α value of -0.4 and a β value of 0.2, consistent with the advice in Chapter 2, Book 3 of ARR2019 (Kuczera & Franks, 2019).

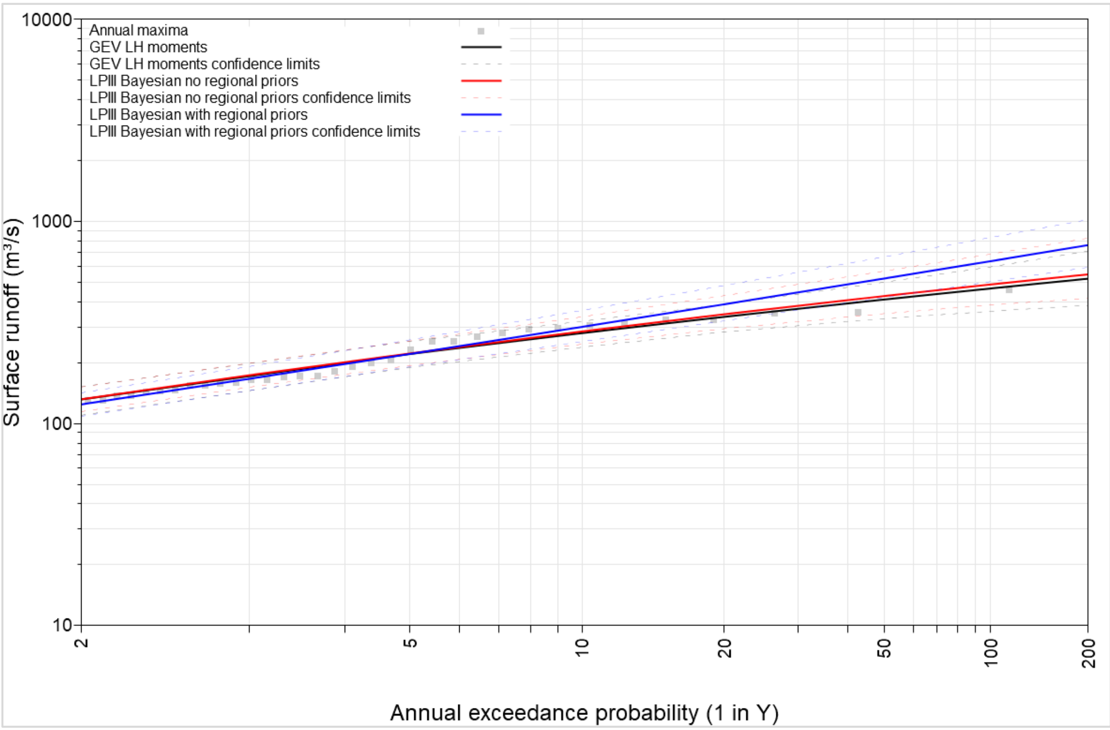
The GEV distribution fitted using LH moments was adopted for this study, as it was considered to provide the best fit overall particularly at the rarer end of the frequency curve. However, these examples demonstrate the differences associated with adopting different flood frequency approaches and highlights the need to undertake any comparisons with reference to the uncertainties involved.



■ **Figure 4-3: Fitted flood frequency comparison – Wando River at Wando Vale**



■ **Figure 4-4: Fitted flood frequency comparison – Boosey Creek at Tungamah**



■ **Figure 4-5: Fitted flood frequency comparison – Mitta Mitta River at Hinnomunjie**

4.3.2 Results

Flood frequency analysis was undertaken for all of the gauge sites considered as part of this project, using the GEV distribution fitted with LH moments. The resulting flood quantiles are summarised in Table 4-3 and plots for all of the fitted flood frequency analyses are shown in Appendix D.

The 1% AEP peak surface runoff quantiles from each of the gauge sites were plotted against catchment area, as shown in Figure 4-6. It can be seen that while there is a clear trend with catchment area (as expected), there is considerable scatter. This emphasizes the degree of variability inherent in flood behavior across a range of catchments which suggests other factors such as landuse, climate and catchment shape could also have an influence.

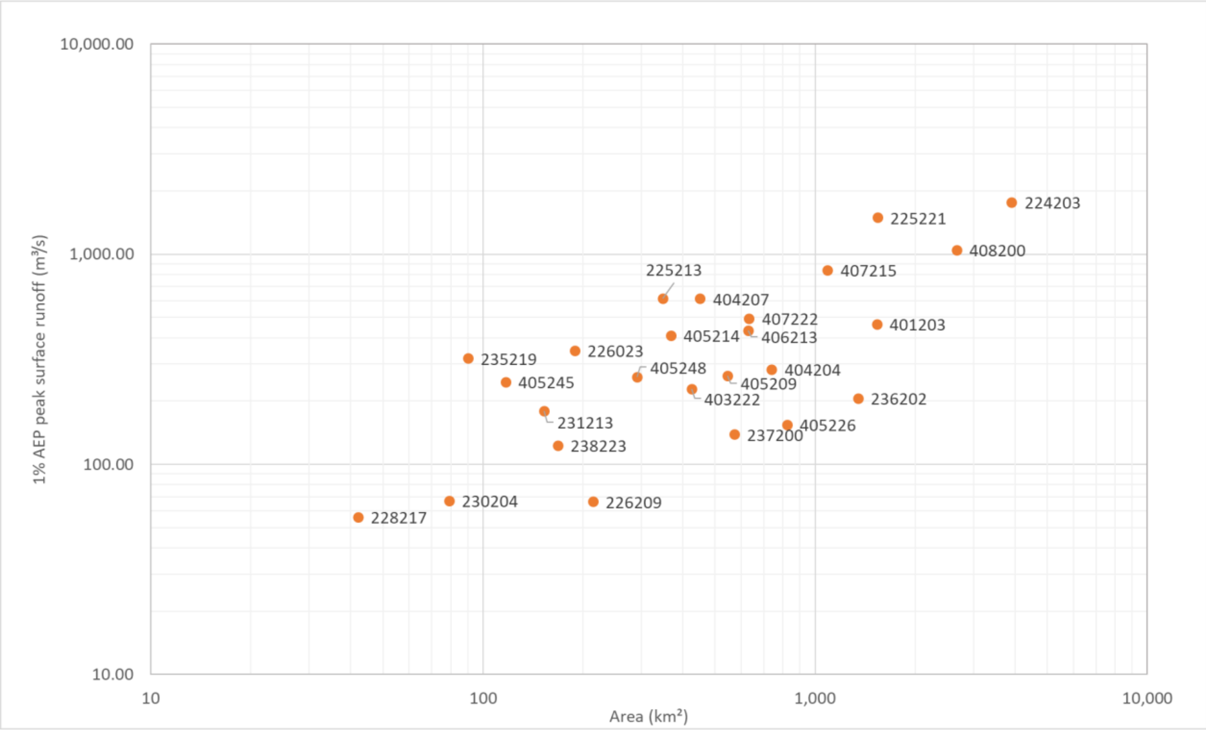


Figure 4-6: Catchment 1% AEP peak surface runoff quantiles verses catchment area

Table 4-3: Flood quantiles for adopted catchments

	Gauge name	% AEP flood quantiles (m^3/s)			
		10	5	2	1
1	Wando River at Wando Vale	57.7	75.7	102	123
2	Moyne River at Toolong	80.5	98.5	122	139
3	Hopkins River at Wickliffe	85.2	118	166	207
4	Aire River at Wyelangta	136	184	256	319
5	Lerderderg River at Sardine Creek Obrien Crossing	106	130	159	180
6	Riddells Creek at Riddells Creek	29.4	39.4	54.3	67.1
7	Toomuc Creek at Pakenham	25.7	33.7	45.7	56.0
8	Moe River at Darnum	46.5	53.5	61.3	66.4
9	Aberfeldy River at Beardmore	203	297	458	614
10	Macalister River at Stringybark Creek	498	714	1,100	1,490
11	Traralgon Creek at Traralgon	95.6	146	242	347
12	Mitchell River at Glenaladale	879	1,130	1,480	1,770
13	Avoca River at Coonooer	385	548	808	1,050
14	Tullaroop Creek at Clunes	163	239	367	493
15	Loddon River at Newstead	373	502	686	839
16	Campaspe River at Redesdale	238	299	376	433
17	Major Creek at Graytown	125	163	217	260
18	Pranjip Creek at Moorilim	84.4	106	134	155
19	Acheron River at Taggerty	96.9	132	197	264
20	Ford Creek at Mansfield	94.5	130	190	247
21	Delatite River at Tonga Bridge	166	223	319	411
22	Boosey Creek at Tungamah	63.3	103	185	282
23	Holland Creek at Kelfeera	212	303	460	614
24	Buffalo River at Abbeyard	92.8	125	178	229
25	Mitta Mitta River at Hinnomunjie	280	337	411	466

5. Design inputs

This section describes the joint probability framework adopted for design flood estimation, and documents the derivation of the key design inputs for each of the 25 catchments.

Design inputs were extracted from the Bureau of Meteorology website and the ARR Data Hub 2019 v1.

5.1 Design flood estimation framework

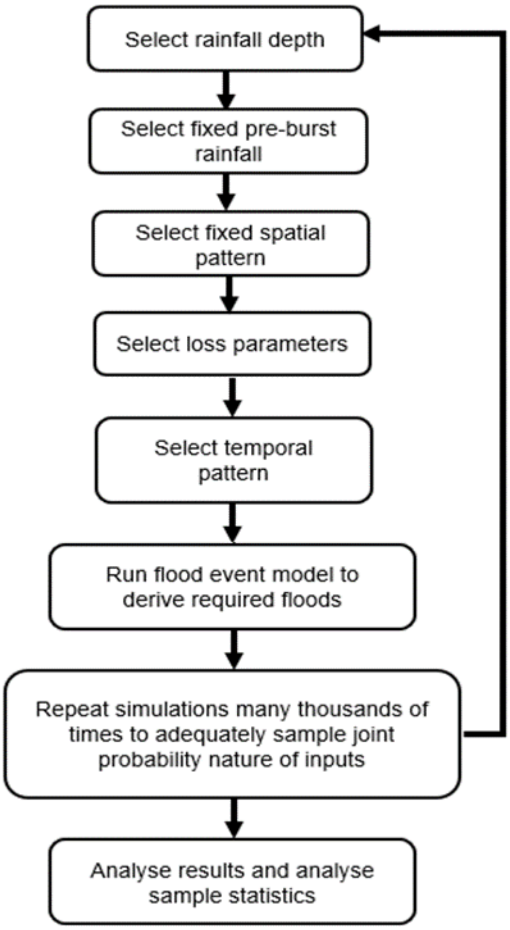
This study adopted a joint probability framework for design flood estimation. This technique recognises that any design flood characteristics (e.g. peak flow) could result from a variety of combinations of flood producing factors, rather than from a single combination. For example, the same peak flood could result from a moderate storm on a saturated catchment, or a large storm on a dry catchment. In probabilistic terms, a 1% AEP flood could be the result of a 2% AEP rainfall on a very wet catchment, or a 0.5% AEP rainfall on a dry catchment. Joint probability approaches attempt to mimic 'mother nature' in that the influence of all probability distributed inputs are explicitly considered, thereby providing a more realistic representation of the flood generation processes.

The method is easily adapted to focus on only those aspects that are most relevant to the problem. For example, it is possible to adopt single 'AEP-neutral' values for some inputs and full distributions for other more important inputs, such as losses and temporal patterns.

The application of joint probability approaches to flood estimation is widely acknowledged to be a more thorough and defensible approach to design flood estimation than the design event approach in Australian practice, and has been incorporated in the ARR2019 (Ball et al., 2019).

The joint probability framework was based on the principles outlined in Nathan et al (2002, 2003) and are summarised in Figure 5-1. In essence the approach involves undertaking numerous model simulations, where the model inputs are sampled from non-parametric distributions.

Simulations were undertaken using a stratified sampling approach in which the sampling procedure focuses selectively on the probabilistic range of interest. Thus, rather than undertake many millions of simulations in order to estimate an event with, say, a 1 in 100 probability of exceedance, a reduced number of simulations were undertaken over a specified number of probability intervals. In this study, the rainfall frequency curve was divided into 100 intervals uniformly spaced over the standardised normal probability domain of AEP's between 1 in 2 and 1 in 2000, and 250 simulations were taken within each division. Thus, a total of 25,000 simulations were undertaken to derive the frequency curve corresponding to each storm duration considered.



▪ **Figure 5-1: Overview of adopted joint probability frameworks**

In developing the joint probability framework particular attention was given to ensuring that the model inputs and the manner in which they were incorporated was consistent with ARR (Ball et al., 2019). The following sections describe the derivation of the main inputs.

5.2 Burst Depth

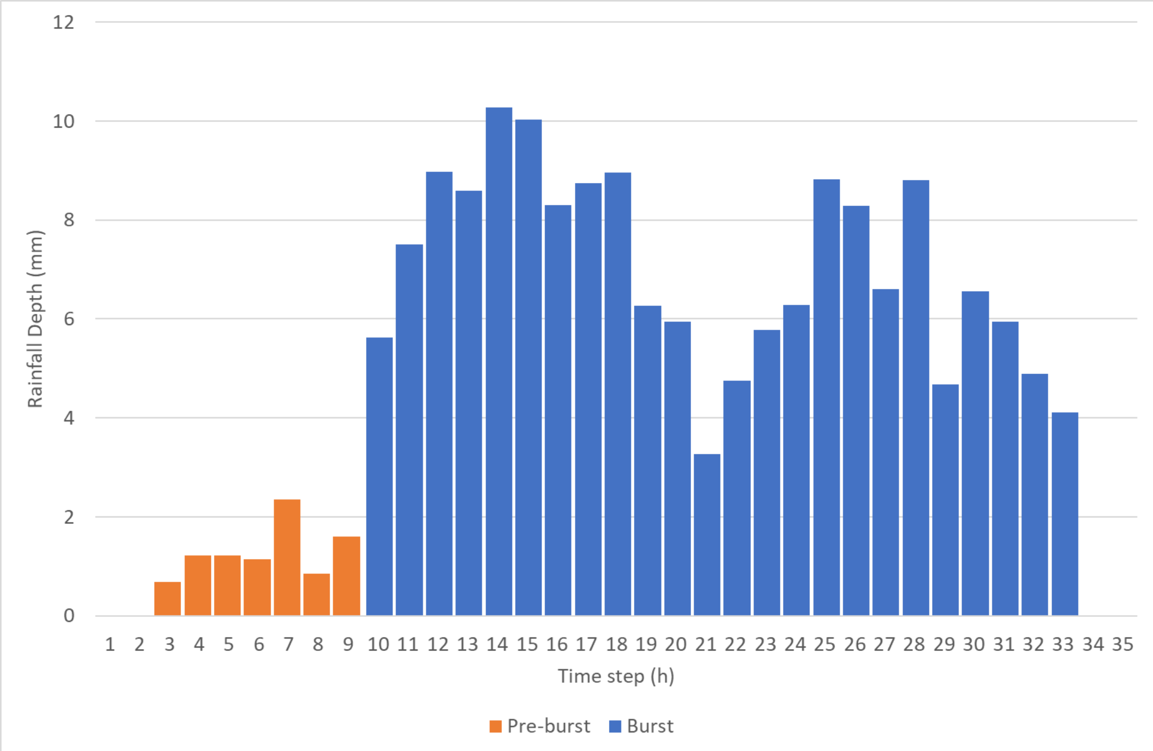
The catchment average point deign rainfall depths were extracted from the Bureau of Meteorology 2016 Intensity-Frequency-Duration (IFD) design rainfalls at the centroid of each RORB model sub-area, as per ARR2019 guidance. This data was extracted for burst durations between 1 hour to 72 hours and AEP's between 50% and 0.05%.

The point rainfall estimates were converted to areal values using the areal reduction factors summarised in Book 2 of ARR2019, as available via the ARR Data Hub. Conceptually, these factors account for the fact that larger catchments are less likely to experience high intensity storms over the whole catchment. In RORBWin, these areal reduction factors were applied to the compete storm.

5.3 Pre-burst

As IFD's are not representative of a complete storm, pre-burst rainfall must be added to be consistent with how the ARR losses were derived. The guidance provided in ARR around pre-burst application is ambiguous and the ARR Data Hub provides both pre-burst depths and ratios. The majority of work on pre-burst undertaken in Australia (e.g Minty and Meighen, 1999 and Jordan et al., 2005) has defined pre-burst as a proportion of the burst rather than an absolute depth. Therefore, for this benchmarking, the pre-burst rainfall is estimated using the median ratio values from the Data Hub. Although this assessment is only focused on AEPs between 10% and 1%, it is recommended that when estimating pre-burst for AEP's rarer than 1% AEP, the Data Hub pre-burst ratio is extrapolated by applying the 1% AEP ratio for rarer AEPs.

The method to extract pre-burst inputs to undertake this assessment was a complete storm approach, where pre-burst rainfall is added to burst rainfall obtained from IFD data. An example of the hyetograph which this approach produces can be seen in Figure 2-1. This figure is an example of the design rainfall for a selected temporal pattern for Mitchell River at Glenaladale. The sensitivity of different approaches to applying pre-burst are discussed in Section 6.2.



- **Figure 5-2: Design rainfall sample for a 24 hour 1% AEP - Mitchell River at Glenaladale**

5.4 Losses

There are two key types of loss models that are typically adopted when modelling design floods:

- Initial loss/continuing loss
- Initial loss/proportional loss

Investigations by Hill et al. (2014) as part of the ARR2019 revision (Hill and Thomson, 2019) were inconclusive as to which loss model works best. Even for catchments where one of the loss models performed better for a majority of events, there were still some events for which the other approach was better. Similarly, there was no obvious relationship between the relative performance of the loss models and hydro-climatic or catchment characteristics.

The advice in ARR is that the initial loss/continuing loss model is most suitable for design flood modelling, because it can be used to estimate flood peaks and volumes for all AEPs. In contrast, it is often difficult to derive unbiased estimates of flood quantiles using the initial loss/proportional loss model over the same range of AEPs. The initial loss/proportional loss model underestimates peak flows for extreme floods if the proportional loss is not varied appropriately with AEP; and to date there is little evidence about how proportional loss varies with AEP. Therefore, for this study an initial loss-continuing loss model was adopted.

The correlation between initial losses and continuing losses is not well understood. Current practice is for initial losses to be sampled from a distribution, while the continuing loss is held constant; this approach was used for the design flood modelling.

Initially, all hydrological models adopted the initial loss and constant continuing loss rate from the ARR Data Hub which were extracted for each of the catchment centroids.

5.5 Spatial patterns

ARR2019 recommends defining a non-uniform design rainfall spatial patterns for all catchments larger than 20 km^2. This should be done using the spatial variability of the design IFD data across the catchment. To apply this in practice, the spatial pattern for the design flood modelling was derived by dividing the 1% AEP point rainfall depth for each RORB model sub-area by the catchment average 1% AEP point rainfall. As such, rainfall was weighted towards those areas of the catchment with relatively higher rainfalls, whilst still maintaining an average rainfall depth across the catchment consistent with the ARR2019 IFD data.

For the purpose of this study, spatial patterns produced for 1% AEP from durations ranging between 1 to 72 hours were adopted. As such, rainfall spatial patterns were assumed to vary with storm duration, but not AEP.

5.6 Temporal patterns

The sample of areal temporal patterns from the catalogue of storms provided in the ARR Data Hub was used for durations between 12 hours and 72 hours, for catchments larger than 75 km^2. For catchments smaller than 75 km^2 and durations between 1 hour and 12 hours, point temporal patterns were adopted. The derivation of these patterns is discussed in ARR2019 (Ball et al., 2019).

Before the temporal patterns were used, they required some smoothing to remove embedded bursts. An embedded burst in a sub-period of rainfall within a given temporal pattern that has a rarer AEP than the actual burst itself. The method described by Scorah et al (2016) was used to filter out the embedded bursts.

5.7 Baseflow

Baseflow was not directly included as a design input. To enable an appropriate comparison to the flood frequency quantiles, the flood frequency analysis was undertaken using an estimate of the surface runoff where the baseflow was subtracted from the streamflow discharge using the digital filter method outlined in Lyne and Hollick (1975). As discussed in Section 4.1, for most catchments baseflow is estimated to be a small proportion of the total flow and therefore the benchmarking results are not expected to be sensitive to the approach adopted for separation of baseflow.

6. Application of ARR2019 to ungauged catchments

This section presents the benchmarking results derived by comparing the modelled design peak flows for each catchment to the estimates from the gauged at-site flood frequency analysis.

6.1 Standard ARR2019 analysis

The calibrated RORB models associated with each of the 25 catchments outlined in Section 3 were run with the design inputs summarised in Section 5. The results were then compared against the flood frequency curves outlined in Section 4.

Comparing the discharge from the RORB models using standard ARR2019 inputs to the gauged at-site flood frequency discharge indicated that there was a systemic underestimation of design peak flow, particularly for more frequent AEPs. This bias is shown in Figure 6-1 using box and whisker plots compiled from the ratio of modelled to gauged peak flow across all 25 catchments. For all AEP events both the mean, represented by the x, and median, represented by the central line, of the ratio of the discharges are less than 1, indicating that the modelled peak flows are biased low.

This ratio is also represented for each individual catchment in Figure 6-2. This highlights that there are some catchments, such as Riddells Creek at Riddells Creek, Acheron River at Taggerty and Buffalo River at Abbeyard, where the rainfall based peak flow estimates derived using the standard ARR2019 inputs tend to overestimate flow. Notwithstanding this, the majority of catchments demonstrate significant underestimates of gauged design peak flows.

These results confirm the main conclusion from previous benchmarking studies conducted by HARC (for Australian large catchments) and WMAwater (2019) (for NSW catchments): use of the standard ARR2019 design inputs tends to underestimate modelled design peak flow between 10% and 1% AEPs when compared to gauged at-site flood frequency analysis.

A summary of the standard ARR2019 modelled design peak flows plotted against the gauged at-site flood frequency quantiles for each of the catchments can be seen in Appendix E.

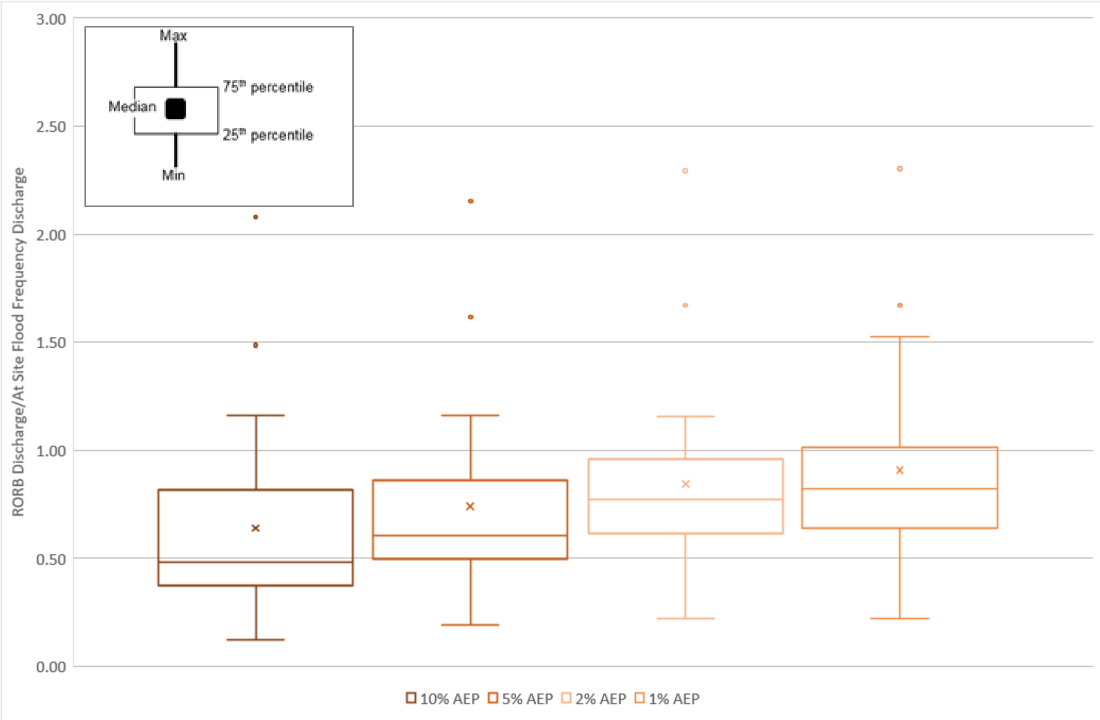


Figure 6-1: Ratio of standard ARR2019 modelled to gauged design peak flow estimates

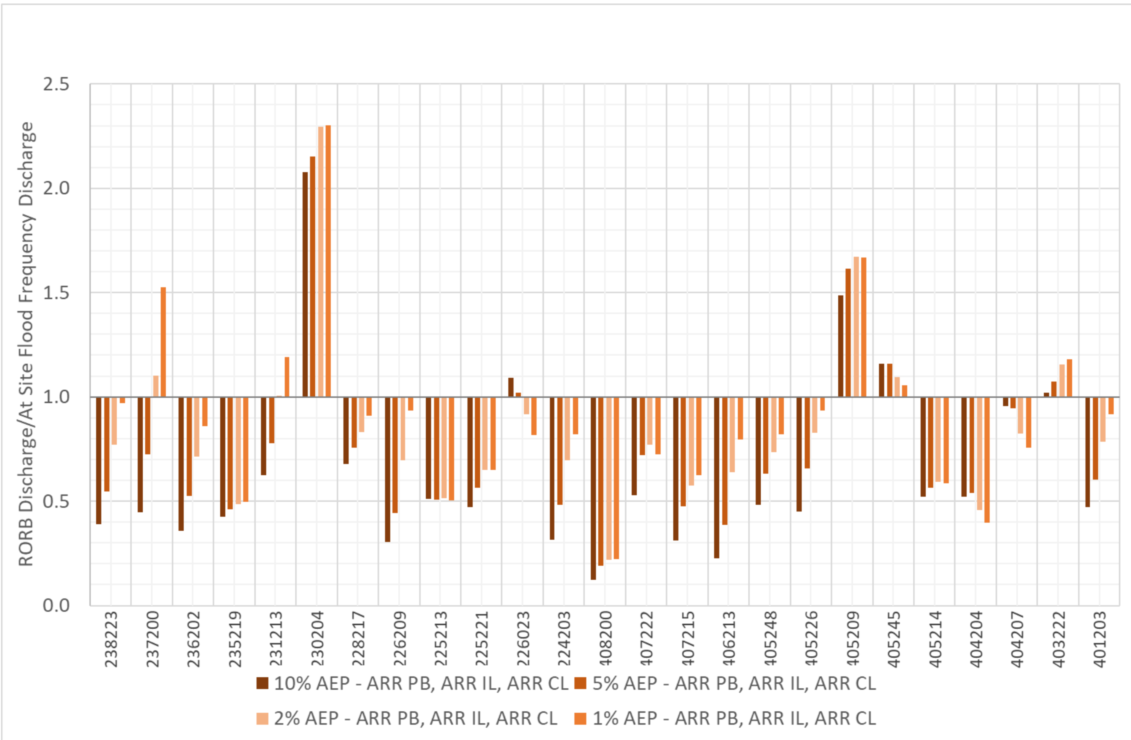


Figure 6-2: Ratio of standard ARR2019 modelled to gauged design peak flow estimates for individual catchments

6.2 Sensitivity to pre-burst rainfall

There is ambiguity in the guidance provided in ARR2019 around the application of pre-burst, in particularly how pre-burst is to be applied temporally and whether the magnitude of pre-burst rainfall should be specified as an absolute depth or via a ratio to the design burst. It is noteworthy that the ARR Data Hub provides pre-burst rainfall magnitude estimates for a range of durations and AEPs (as well as several exceedance probabilities) in both depths and ratios.

As a result, a sensitivity analysis was undertaken to test additional methods to account for the rainfall antecedent to the main burst. These methods were selected based on standard industry application. The three different methods analysed are outlined below:

- ARR pre-burst ratios - A complete storm approach, where pre-burst rainfall is added to burst rainfall obtained from IFD data. The pre-burst rainfall depth is estimated using the median ratio values from the Data Hub. For Monte Carlo simulations sampling events rarer than 1% AEP, the 1% AEP pre-burst ratio was held constant. As the ARR Data Hub doesn't provide pre-burst rainfall temporal patterns, pre-burst rainfall temporal patterns estimated by Minty and Meighen (1999) for pre-bursts greater than 12 hours and Jordan et al. (2005) for pre-bursts less than 12 hours were adopted. This method was used to derive pre-burst design inputs for the 'standard ARR2019' analysis reported in Section 6.1.
- ARR pre-burst absolute values - A burst approach, where the median pre-burst depths from the Data Hub, averaged between 10% AEP and 1% AEP, were subtracted from the median initial loss obtained from the Data Hub. For Monte Carlo simulations sampling events rarer than 1% AEP, the 1% AEP pre-burst depth was held constant. If the pre-burst exceeds the initial loss then the remaining pre-burst rainfall is ignored. This process calculates a burst initial loss, which is then used along with the burst depth obtained from the IFD values. This approach does not require the pre-burst temporal pattern to be specified.
- Bureau of Meteorology pre-burst ratios - A complete storm approach, where pre-burst rainfall is added to burst rainfall obtained from IFD data. The pre-burst rainfall depths were estimated using methods by the Bureau of Meteorology as documented in Minty and Meighan (1999) and Jordan et al. (2005). The pre-burst ratios adopted were held constant for all AEPs. Pre-burst rainfall temporal patterns estimated by Minty and Meighen (1999) and Jordan et al. (2005) were adopted.

These different pre-burst approaches are also represented conceptually through hyetographs in Figure 6-3.

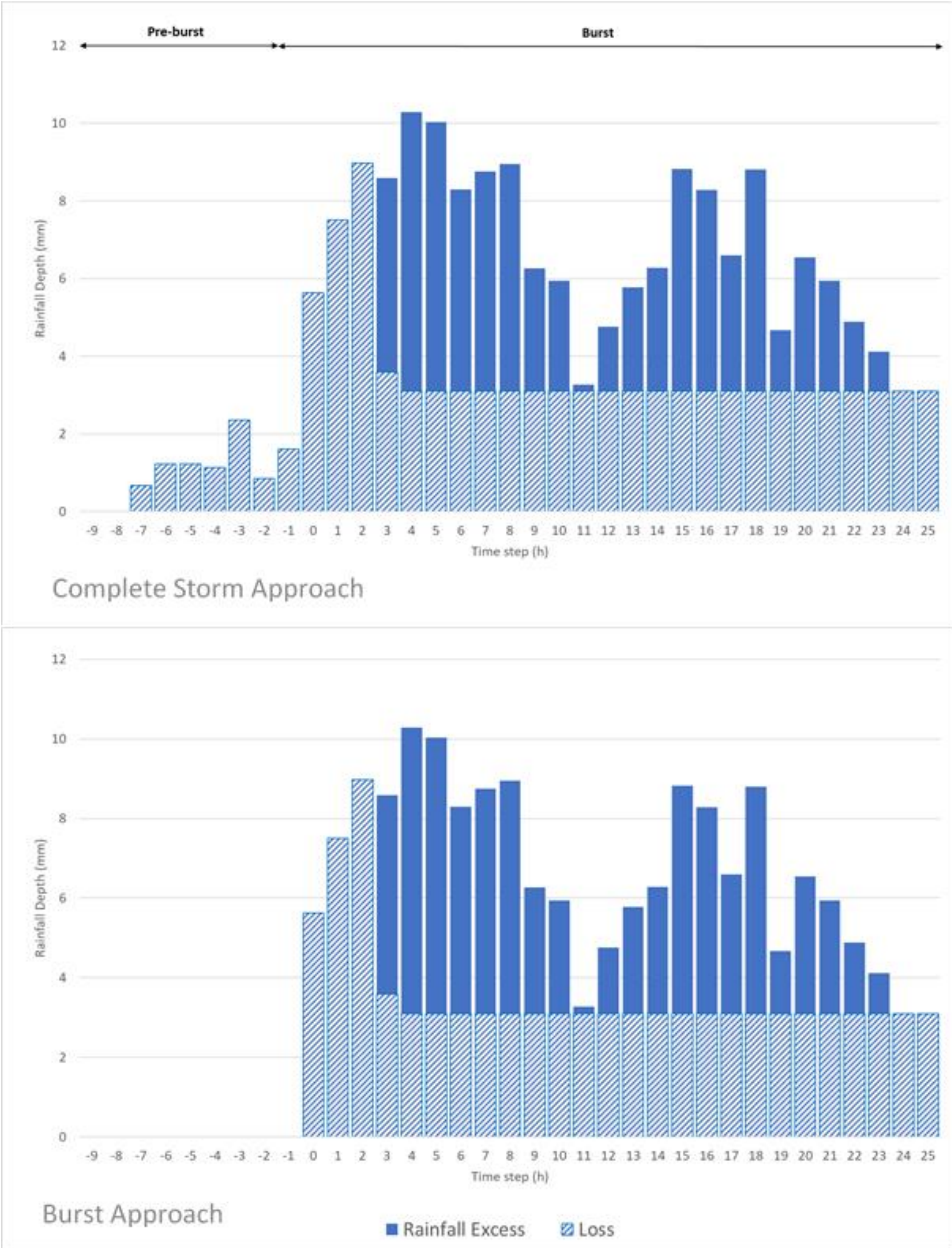
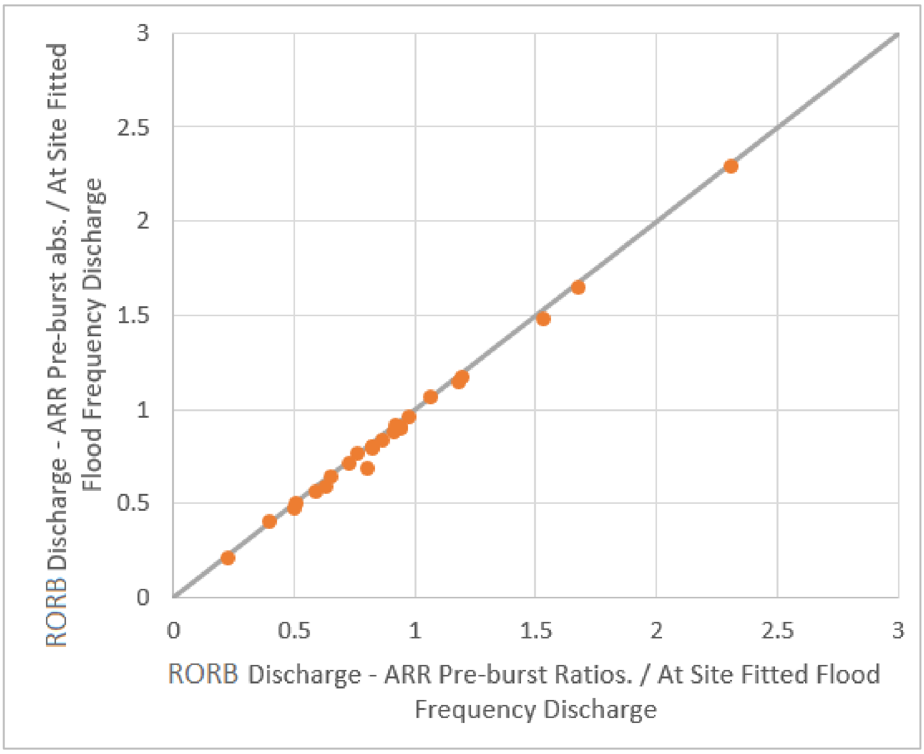
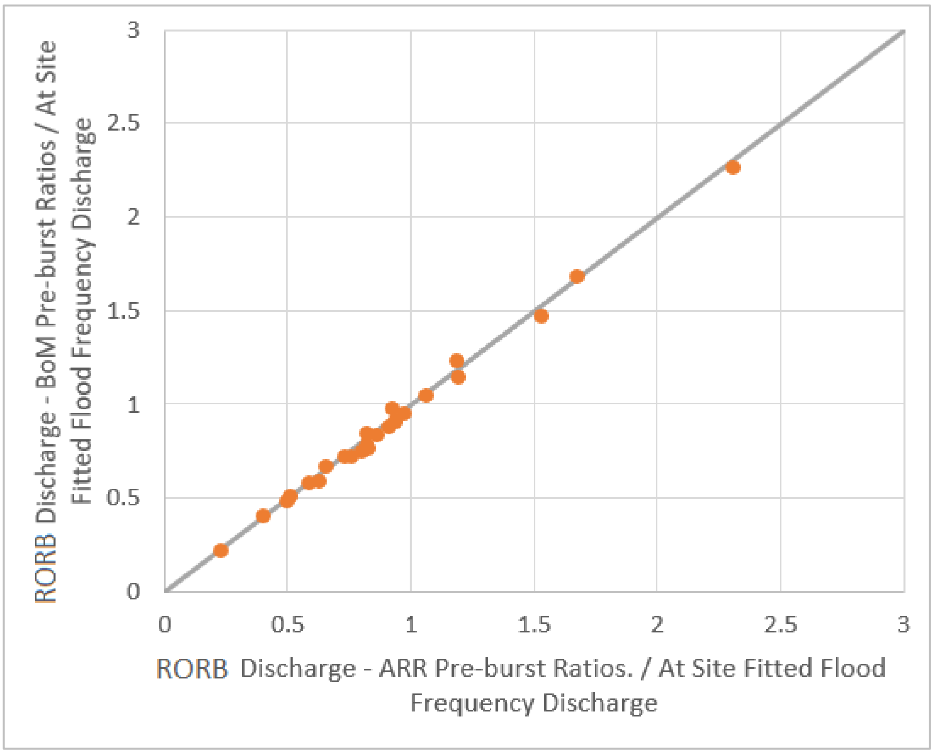


Figure 6-3: Conceptual hyetographs of different pre-burst approaches

All catchments were run with the three pre burst approaches outlined above. The results indicated there was minimal variation in peak flow estimates up to the 1%. This is highlighted in Figure 6-4 and Figure 6-5 which compare the ratio of design peak flow estimates derived using the three pre-burst approaches. It can be seen that there is negligible variation about the one-to-one line in each plot, indicating that choice of pre-burst approach is having minimal influence on the peak flow estimates.



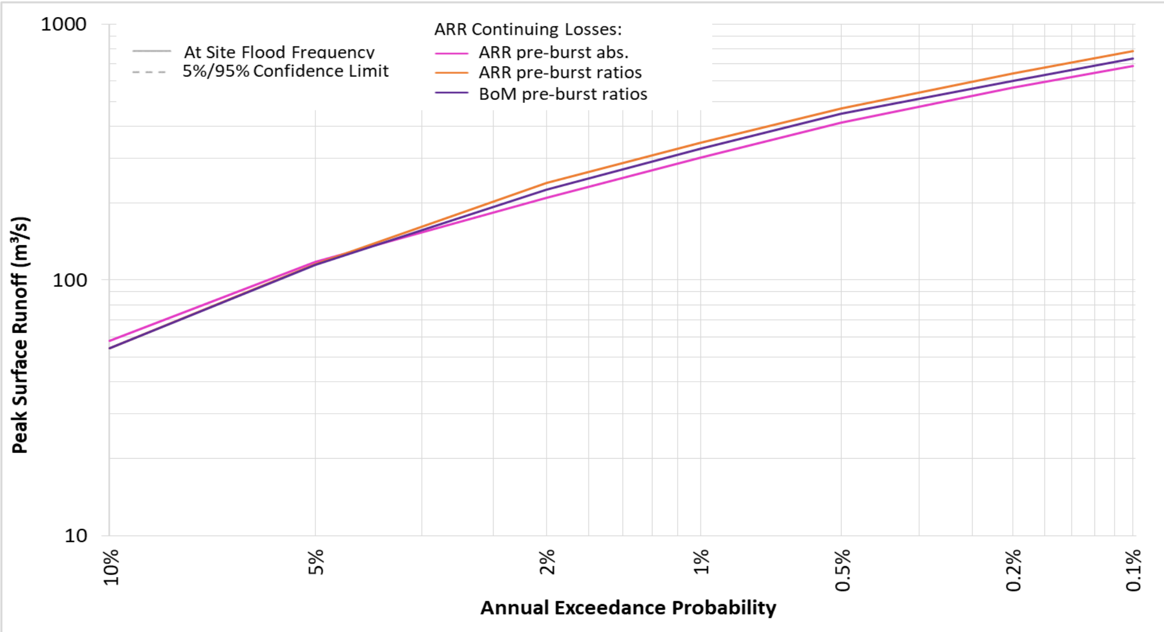
- **Figure 6-4: Comparison of ARR pre burst ratio approach with ARR pre-burst absolute for a range of 1% AEP**



- **Figure 6-5: Comparison of ARR pre burst ratio approach with BoM pre-burst approach for a range of 1% AEP**

Whilst this conclusion may seem to indicate that the method selected to treat pre-burst variability is of marginal relevance, there are several other factors which should be considered. The following points are relevant:

- Previous studies such as Minty and Meighen (1999) and Scorah (2015) have demonstrated that the pre-burst increases as the bursts become rarer and therefore it is difficult to define the value of pre-burst as an absolute magnitude. However, when expressed as a ratio of the pre-burst to burst depth, both studies found that the ratio was invariant with AEP. Thus, expressing pre-burst as a ratio rather than an absolute value is more appropriate for design flood estimation where design flood estimates are required over a range of AEPs. It is noted that there is significant variability in the Data Hub estimates of pre-burst rainfall, due to sampling variability. As such, consistent trends in pre-burst data with AEP are not necessarily present in the Data Hub values for a given location.
- Careful definition of pre-burst magnitude is particularly important when the focus of flood estimates is on rare and extreme events. As can be seen from the example shown in Figure 6-6, the design peak flows obtained using the different pre-burst approaches tend to diverge as AEP becomes rarer. As such, when looking at design flood estimates for AEPs rarer than 0.1%, it is critical that the pre-burst depth be allowed to increase in some reasonable manner as AEP becomes rarer.
- In relation to pre-burst temporal pattern, the results presented here have demonstrated that specific definition of pre-burst rainfall temporal pattern may be of marginal relevance for many applications. This is particularly and obviously the case where the magnitude of the pre-burst for a given storm duration and AEP is less than the randomly sampled initial loss value applied. This is a common for Victorian catchments in many cases, but care must be taken with this approach as AEP becomes increasing rare. Care is also required where the median initial loss is relatively low or initial loss variability is sampled in a joint probability framework.
- There are a number of specific cases where pre-burst temporal variability should be specified explicitly. These include urban catchments (where due to imperviousness, significant runoff may occur during the pre-burst phase) and catchments with significant storages (where the volume generated from pre-burst rainfall excess may be important). Where the focus is on flood estimation for AEPs rarer than about 1%, it is also recommended that pre-burst temporal pattern is specified, as the pre-burst magnitude will tend to increase with rarer AEPs whilst the initial loss value does not. In other cases, it may be acceptable to ignore pre-burst temporal variability and simply adjust the applied initial loss value to represent a burst initial loss.
- The sensitivity analysis is considered sufficient to conclude that the estimates of the 1% AEP peak flow are not sensitive to the different definitions of pre-burst. However, it should be noted that the analyses only considered peak flows and could be extended to include flow volumes in future work. Alternate definitions of pre-burst could also be considered.



- **Figure 6-6 : Campaspe River at Redesdale application of pre-burst for rarer AEPs**

6.3 Spatial variability in regional losses

As noted in Section 2.4, the regional median storm initial loss and continuing loss values for rural catchments provided by ARR2019 were estimated for four regions of hydrologic similarity which were defined across Australia. These regions each have different prediction equations used for deriving loss estimates based on independent variables such as soil moisture storage, potential evapotranspiration and catchment slope. It should be noted that there were only 35 catchments used in the analyses and so there was a small number in each of the 4 regions.

Figure 6-7 outlines these defined loss regions within Victoria and the location of the 25 catchments in regards to these regions. It highlights that the majority of the 25 catchments adopted for this study (and much of Victoria) sit within region 3. There are also areas of both regions 2 and 4 within Victoria. Some of the selected catchments within this study do sit close to or partially within regions 2 or 4, such as the Mitchell River at Glenaladale.

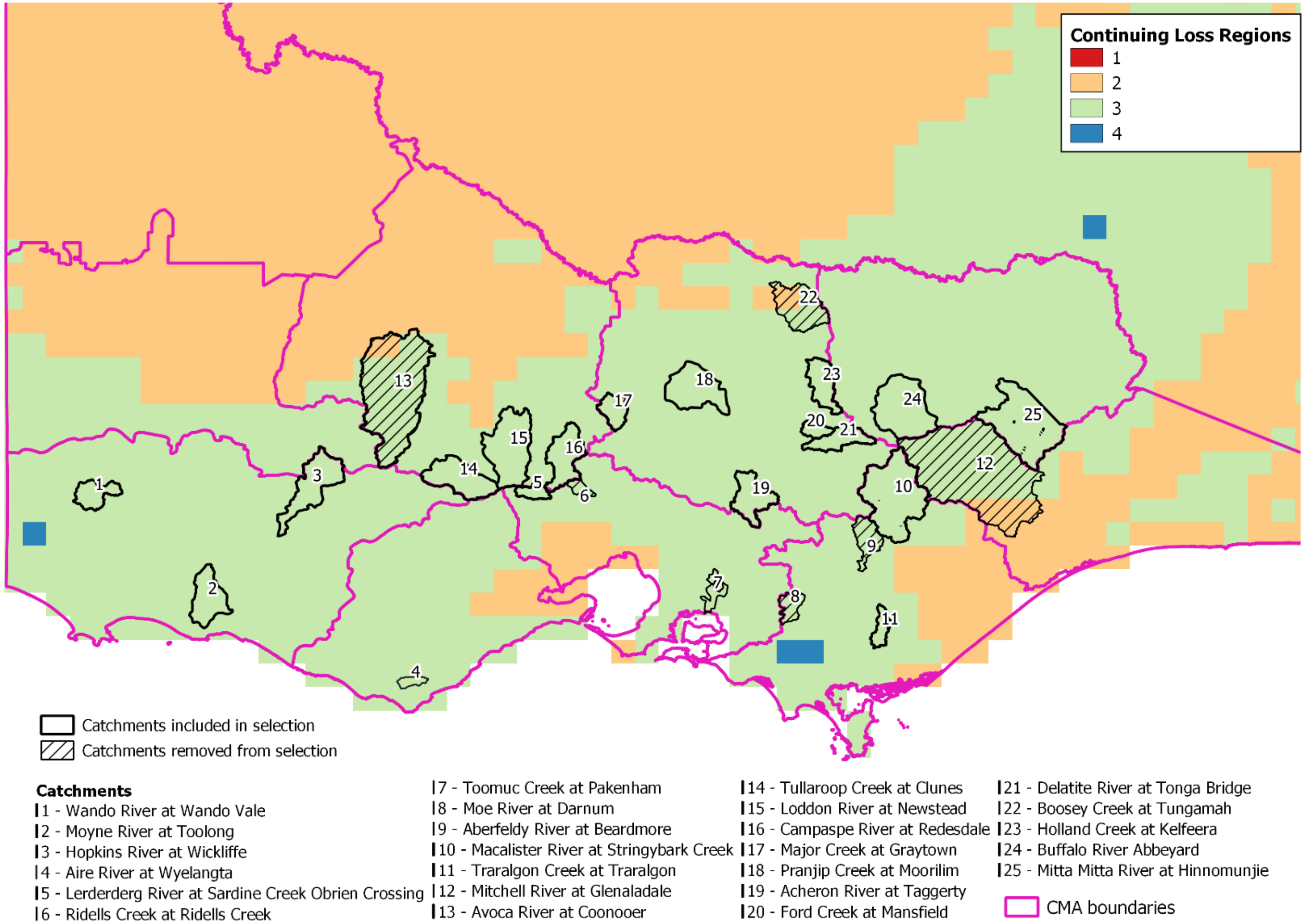


Figure 6-7: ARR loss regions for Victoria showing catchments potentially impacted by smoothing between regions

ARR2019 used the prediction equations to derive gridded estimates of both initial loss and continuing loss across Australia. To manage the potentially large difference in loss estimates as the prediction equations changed between the interface of each region, smoothing was applied. ARR2019 Book 5 Chapter 3 outlines that the gridded values were smoothed using a window of 45 km x 45km. The application of this smoothing procedure to produce a loss grid which is used in the ARR Data Hub can be seen in Figure 6-8. This figure highlights that as well as catchments crossing multiple regions, those sitting close to a region boundary may be affected by smoothing of losses across that boundary. This effect could result in significant spatial variability of the estimated loss values for that catchment.

To investigate the potential impact these loss regions were having on the analysis, catchments which could be influenced by the smoothing between regions were removed from the analysis. To objectively define which of the 25 catchments may be affected by this issue, the continuing loss was calculated at the centroid of each catchment and then as a spatially averaged value across each catchment. The difference between these two values was then compared, and those catchments which exhibited large variations (8% or more) in continuing loss values and were situated within or close to an alternative loss region were removed from the analysis. This was done on the basis that smoothing of regional loss estimates across the region boundaries may be biasing the analysis.

The six highlighted catchments in Table 6-1 were the ones which were removed from the analysis. It is noteworthy that the Aire River at Wyelangta did exhibit a variation of 8 %. However, it was not excluded from the analysis as it was not in close proximity to an alternative loss region. The variability in loss estimates within the Aire River catchment is likely a result of unusual topographic and soil moisture characteristics of the Otway region.

The refined list of 19 catchments were then used to re-create the box and whisker plots comparing the ratio of modelled to gauged design peak flow estimates previously shown as Figure 6-1 and Figure 6-2. Figure 6-9 and Figure 6-10 highlight the removal of the six catchments which may be influenced by other regions significantly reduces the variability of the bias (i.e. the vertical length of the box and whiskers), whilst still demonstrating systematic underestimation of the peak flows for all AEPs.

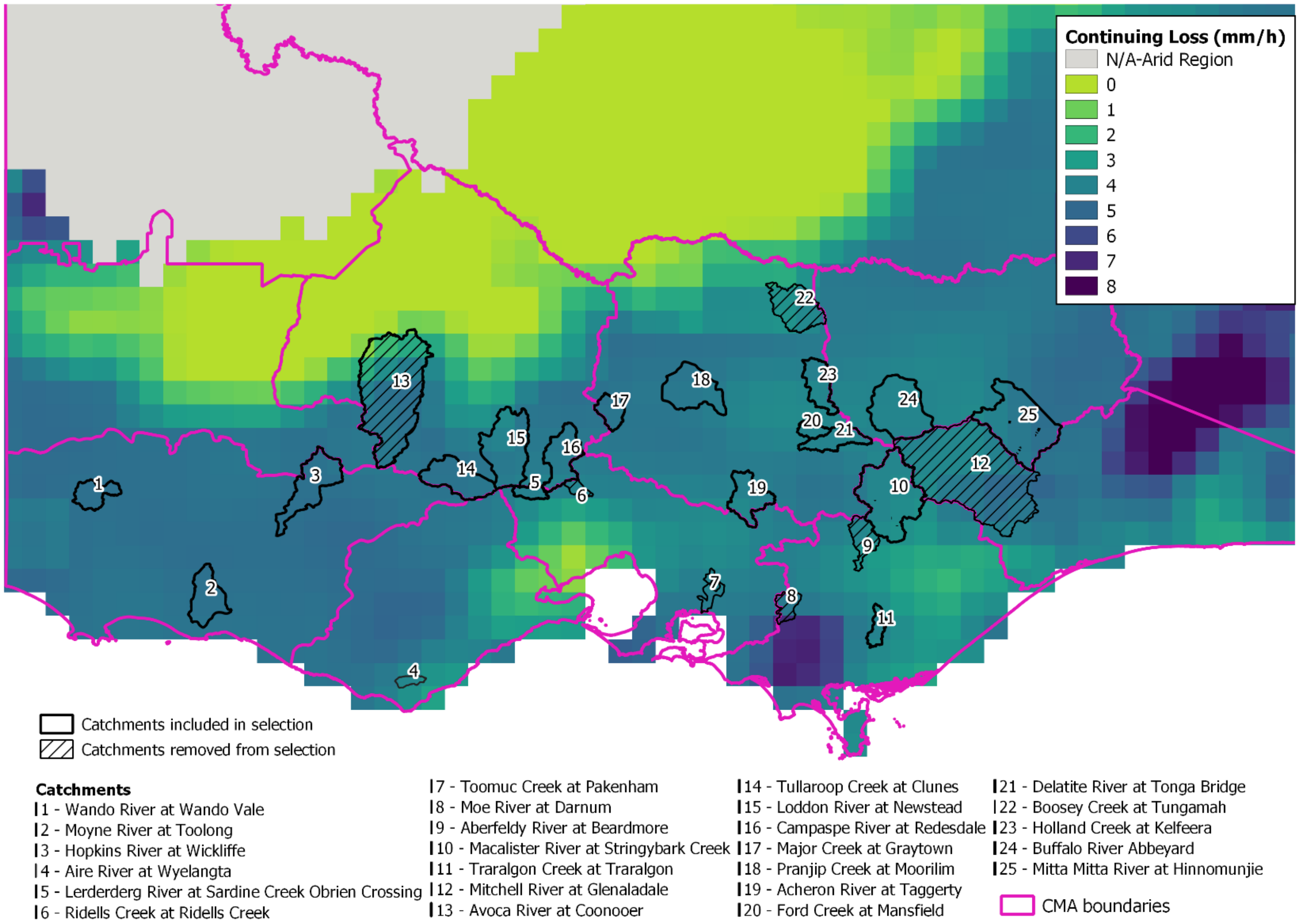
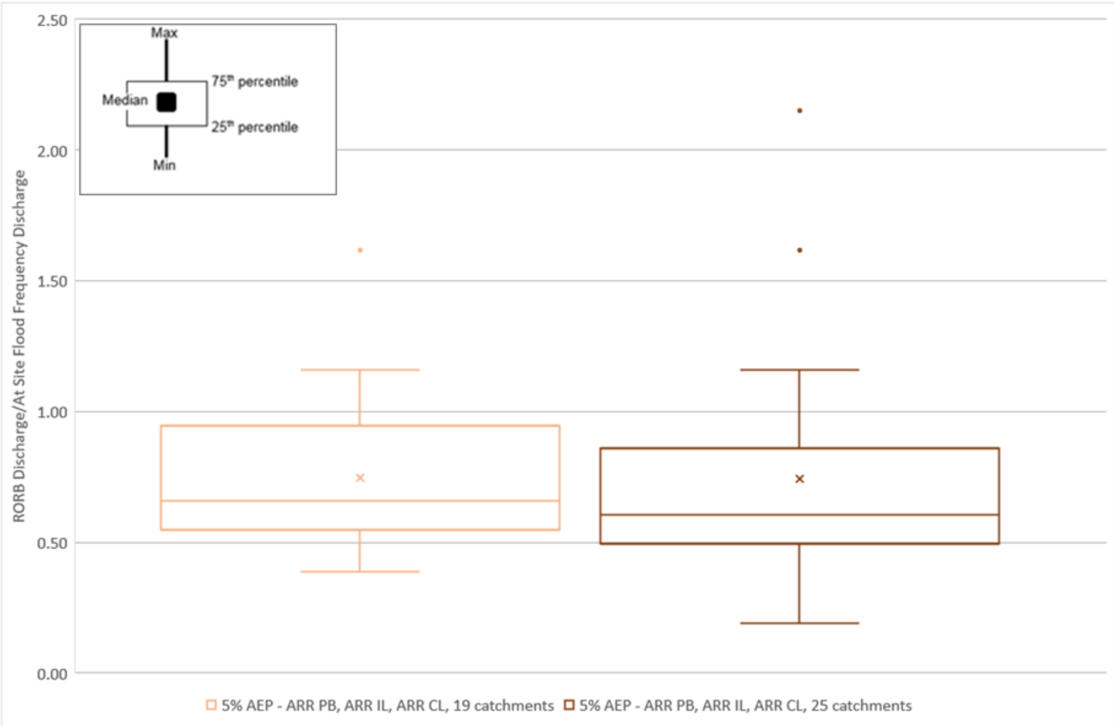


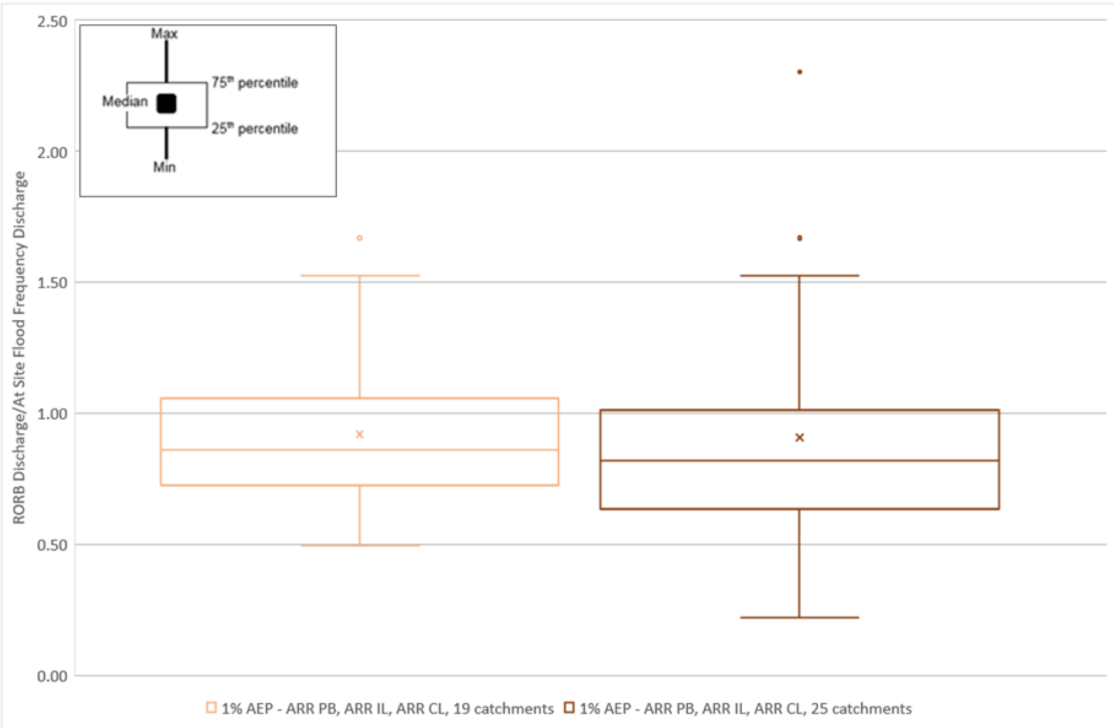
Figure 6-8: Gridded ARR2019 rural continuing loss estimates

Table 6-1: Variation in regional continuing loss estimates for all catchments

	Gauge name	Centroid CL (mm/h)	Catchment avg. CL (mm/h)	Difference in CL (abs %)
1	Wando River at Wando Vale	4.6	4.7	3
2	Moyne River at Toolong	4.6	4.6	1
3	Hopkins River at Wickliffe	4.7	4.7	0
4	Aire River at Wyelangta	3.8	4.1	8
5	Lerderderg River at Sardine Creek Obrien Crossing	3.7	3.7	1
6	**Riddells Creek at Riddells Creek**	**2.9**	**2.7**	**8**
7	Toomuc Creek at Pakenham	4.3	4.4	3
8	**Moe River at Darnum**	**5.6**	**6.9**	**19**
9	**Aberfeldy River at Beardmore**	**3.7**	**3.5**	**8**
10	Macalister River at Stringybark Creek	3.8	3.9	4
11	Traralgon Creek at Traralgon	4.0	4.2	7
12	**Mitchell River at Glenaladale**	**3.9**	**4.3**	**9**
13	**Avoca River at Coonooer**	**4.0**	**4.5**	**11**
14	Tullaroop Creek at Clunes	4.5	4.5	0
15	Loddon River at Newstead	4.3	4.4	1
16	Campaspe River at Redesdale	3.9	4.0	2
17	Major Creek at Graytown	4.5	4.4	1
18	Pranjip Creek at Moorilim	4.4	4.4	1
19	Acheron River at Taggerty	3.9	3.8	3
20	Ford Creek at Mansfield	4.1	4.4	6
21	Delatite River at Tonga Bridge	4.2	4.3	3
22	**Boosey Creek at Tungamah**	**3.9**	**3.4**	**13**
23	Holland Creek at Kelfeera	3.9	3.8	3
24	Buffalo River at Abbeyard	4.0	4.0	1
25	Mitta Mitta River at Hinnomunjie	4.2	4.1	4



- **Figure 6-9: Ratio of standard ARR2019 modelled to gauged 5% AEP design peak flow estimates for all catchments vs retained catchments**



- **Figure 6-10: Ratio of standard ARR2019 modelled to gauged 1% AEP design peak flow estimates for all catchments vs retained catchments**

7. Application of ARR2019 to gauged catchments

The results presented in Section 6 were produced for the purposes of benchmarking; the regional loss estimates were adopted as supplied from ARR2019 without being adjusted to reconcile the modelled and gauged flood frequency estimates. As per the advice in Section 2.2.2 and ARR2019 Book 5, where gauged streamflow and rainfall data is available within the catchment, adjustment of both median initial and continuing loss values to achieve reconciliation between the modelled and gauged design flood estimates should be undertaken. If reasonable rainfall and streamflow records are available in catchments in close proximity, an empirical analysis to estimate losses is also recommended. Loss values achieved through these approaches are conceptually regarded as more defensible than the regional estimates provided by ARR2019, although consideration must be given to the reliability of the gauged streamflow data and suitability of data between catchments in close proximity.

7.1 Examples of reconciliation to gauged design flood estimates

As noted previously, application of the standard ARR2019 design inputs systematically underestimates gauged design peak flows in Victorian catchments. To further understand the cause of this bias, a partial model verification procedure was undertaken for each catchment. This involved adjusting the adopted continuing loss value for each model such that an optimal reconciliation was achieved between the modelled and gauged design peak flow estimates.

Note that this approach is described as a partial verification because only the continuing loss value was adjusted; the regional median initial loss values were retained as provided from the ARR Data Hub. This was done so that only the value of one variable was changing to enable the investigation of its impact on the bias. Continuing loss was selected for this analysis based on the outcomes of the recent WMAwater benchmarking study for NSW catchments. This work concluded that an adjustment factor should be applied to the ARR2019 regional continuing loss estimates as a way to mitigate systemic underestimation of design peak flows. There was therefore some interest in assessing whether a similar approach could be applied for Victoria.

An example of the outcome of the reconciliation of continuing losses for selected catchments can be seen in Figure 7-1 to Figure 7-4. These results demonstrate that reconciliation between gauged and modelled design flood estimates can be readily achieved in most cases, using physically reasonable estimates of losses. Importantly, these loss values are also invariant with AEP and duration (i.e. the same initial loss and continuing loss values have been adopted for all AEPs), as would be conceptually expected.

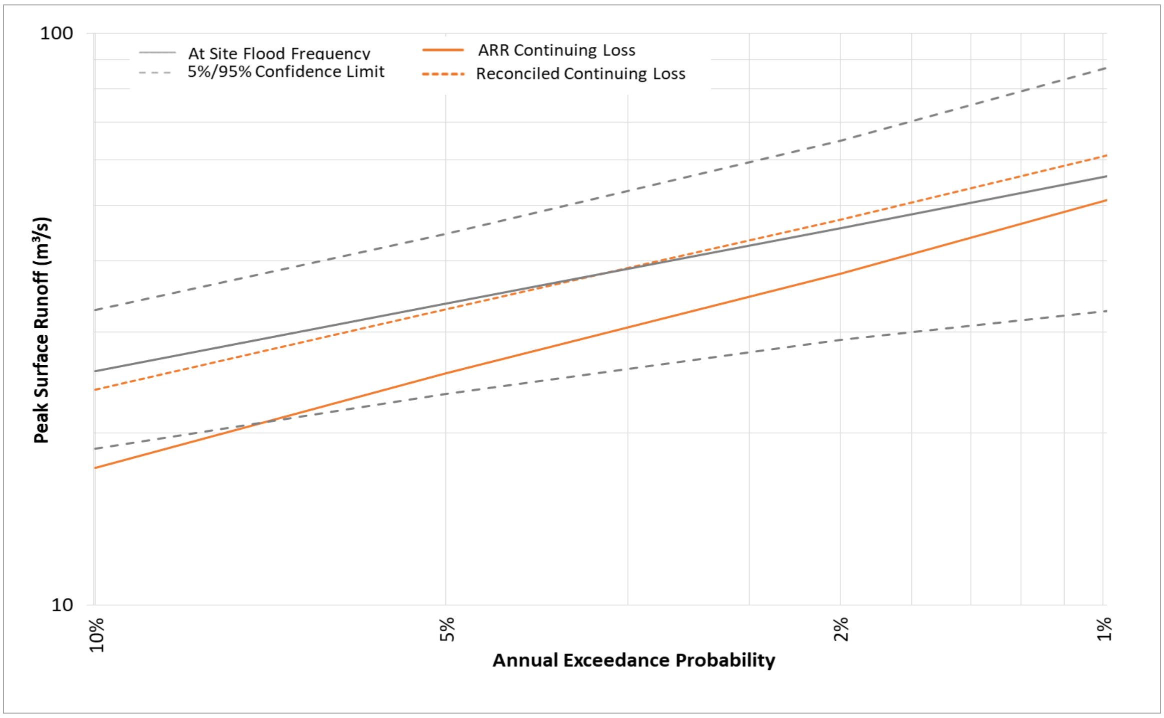


Figure 7-1: Flood estimates using adjusted continuing loss for Toomuc Creek (228217)

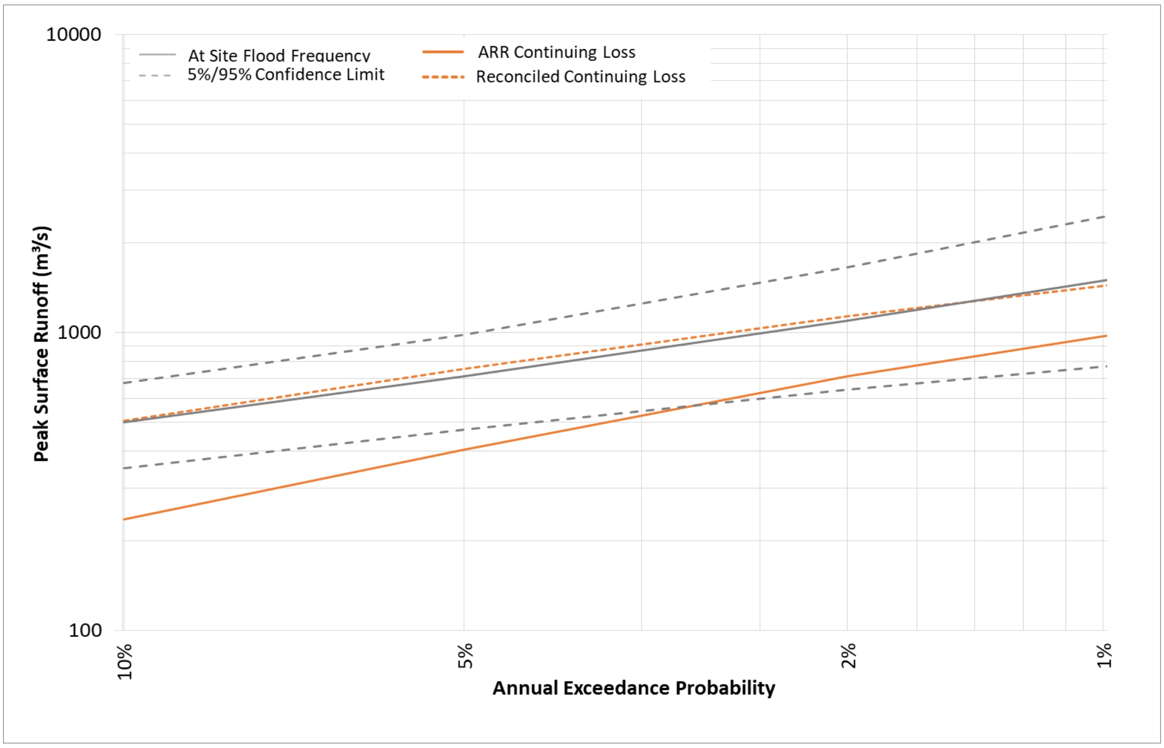
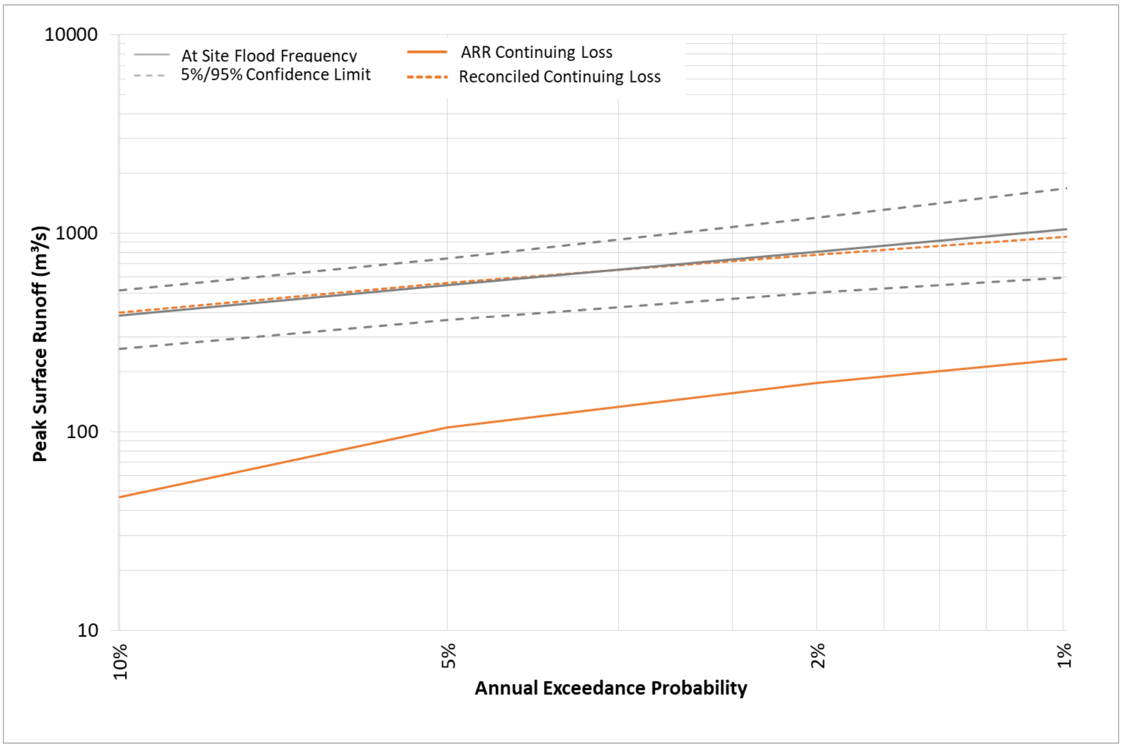
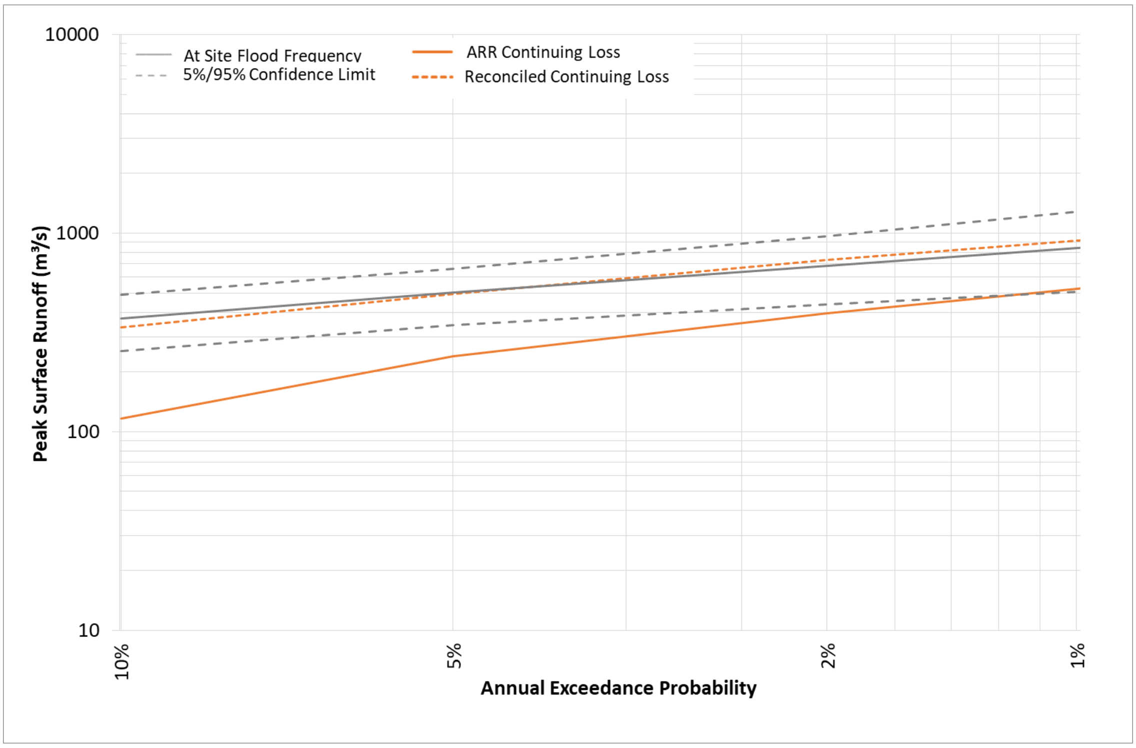


Figure 7-2: Flood estimates using adjusted continuing loss Macalister River (225221)



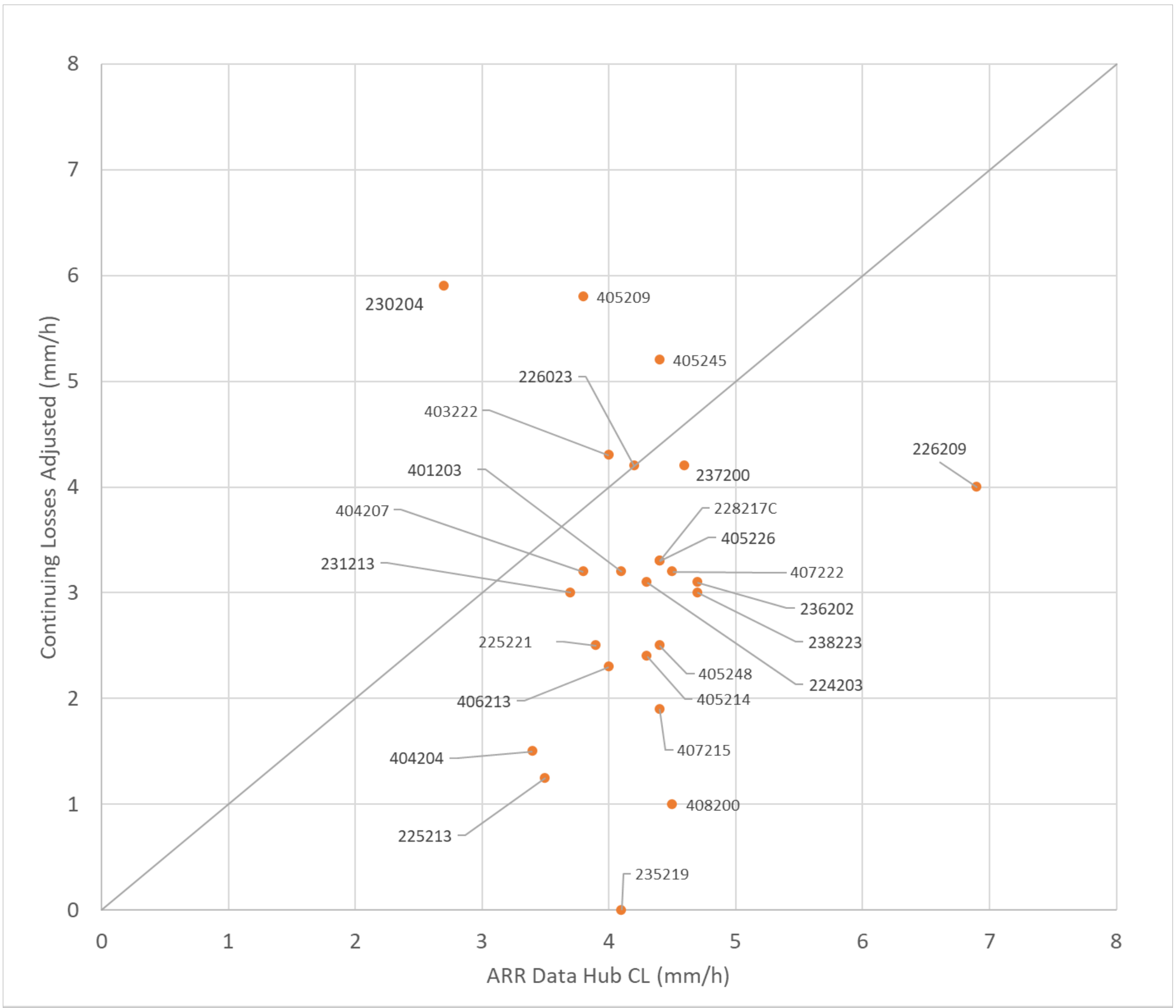
- Figure 7-3: Flood estimates using adjusted continuing loss for Avoca River (408200)



- Figure 7-4: Flood estimates using adjusted continuing loss for Loddon River (407215)

7.2 Summary of adjusted continuing loss values

The adjustment of continuing loss values to optimise the fit between the gauged and modelled flood frequency estimates for all 25 catchments indicated there was no clear trend. This is highlighted in the scatter present when comparing the reconciled continuing loss value to the ARR Data Hub continuing loss value in Figure 7-5. It can be seen that on average, the fitted continuing loss values are slightly lower than the regional values, however there is insufficient evidence to warrant adoption of an adjustment factor.



■ **Figure 7-5: Comparison of reconciled continuing loss vs the Data Hub continuing loss**

The above results demonstrate that it is difficult to identify a single adjustment to continuing loss that addresses the bias in design flood estimates observed in Section 6. As such, consideration was given to other potential approaches to correct the bias observed in the modelled design flood results.

8. Potential methods for bias correction

As noted in Section 6, when the standard ARR2019 inputs are applied, there is a systemic underestimation in modelled design flood estimates when compared to gauged estimates. For this project, preliminary investigations into a number of approaches to mitigate this bias were undertaken. These approaches investigated were selected based on:

- Existing approaches adopted within other states of Australia
- Insights gained from the results outlined in Sections 6 and 7
- Ease of use, i.e. the ability for any bias correction approach to be easily adopted by practitioners based on existing ARR Data Hub information

Due to the uncertainties raised in Section 6.3 associated with the spatial variability of regional loss estimates, these approaches were only analysed on the refined list of 19 catchments which are wholly within region 3 and not subject to significant spatial variability in losses. All results presented within this section are based on the subset of catchments identified within Section 6.3. Therefore, all recommendations resulting from this analysis are only applicable to catchments which are wholly within region 3.

The following sections outline each approach investigated and the results from the analysis.

8.1 Continuing loss adjustment

This approach was based on work undertaken in 2019 by WMAwater, which found that when standard ARR2019 design inputs were used to prepare rainfall-based design flood estimates for 180 gauged catchments in NSW, the results underestimated design peak flow. Many of the standard design inputs, such as rainfall IFD, temporal patterns and regional loss estimates which have been used for the current study were also used in the WMAwater 2019 assessment. WMAwater (2019) then optimised initial and continuing losses to reconcile modelled design peak flows to the results of gauged at-site flood frequency analysis. Though it is noted that a key difference between these two studies is that WMA used regional estimates of routing parameters whereas this study has used calibrated models.

Based on the outcome of this reconciliation, WMAwater concluded that the simplest and most efficient method of bias correction, if no other option to use calibrated or reconciled losses was available, was a blanket adjustment factor to be applied to the regional continuing loss values. It was concluded that an adjustment factor of 0.4 should be adopted for all regional continuing loss estimates across all NSW catchments. This advice was then released to practitioners via jurisdiction specific guidance on the ARR Data Hub.

As similar inputs have been used for the current study, application of a multiplication factor of 0.4 to the regional continuing loss estimates was analysed as a potential bias correction approach for Victorian catchments. The results indicated that this approach overcorrected the bias observed in design flood estimates for the 19 catchments of interest.

When comparing the ratio of modelled to gauged design peak flow estimates, the 0.4 continuing loss factor approach significantly overestimated both average and median peak flow. Modelled median peak flows were close to 1.5 times the gauged estimates for the 19 catchments analysed, as compared to median ratios between 0.6 and 0.8 derived using the standard ARR2019 design inputs. This can be seen in the 5% AEP and 1% AEP box and whisker plots in Figure 8-1 and Figure 8-2, which compare these ratios. Figure 8-2 also indicated, particularly for the 1% AEP event, a significantly larger spread of variability in results compared to standard ARR2019 modelled design peak flows. The results for each individual catchment, for the 5% AEP and 1% AEP, are also seen in Figure 8-3 and Figure 8-4.

Though this outcome highlighted that a continuing loss factor of 0.4 was not appropriate for Victorian catchments, another adjustment factor could have provided a more favourable outcome. However, this was not tested as the analysis highlighted that even though a different factor may result in the median and average values providing a ratio closer to 1, it would not reduce the increased spread of variability in results that this approach provides.

As such, it was concluded that the approach of applying a uniform adjustment factor of 0.4 to the ARR2019 regional continuing loss estimates is not an appropriate technique for treating bias in modelled peak design flows for Victorian catchments within the influence of loss region 3.

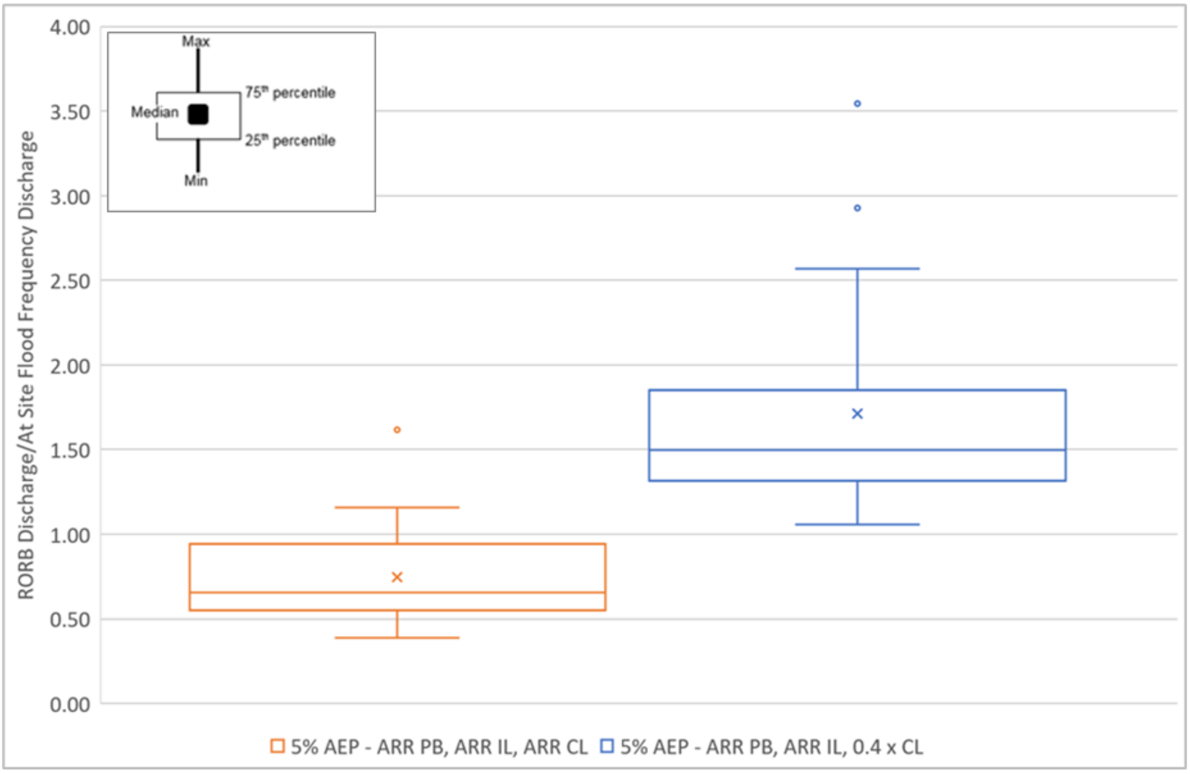


Figure 8-1: 5% AEP peak flow ratios standard ARR2019 vs 0.4 CL factor

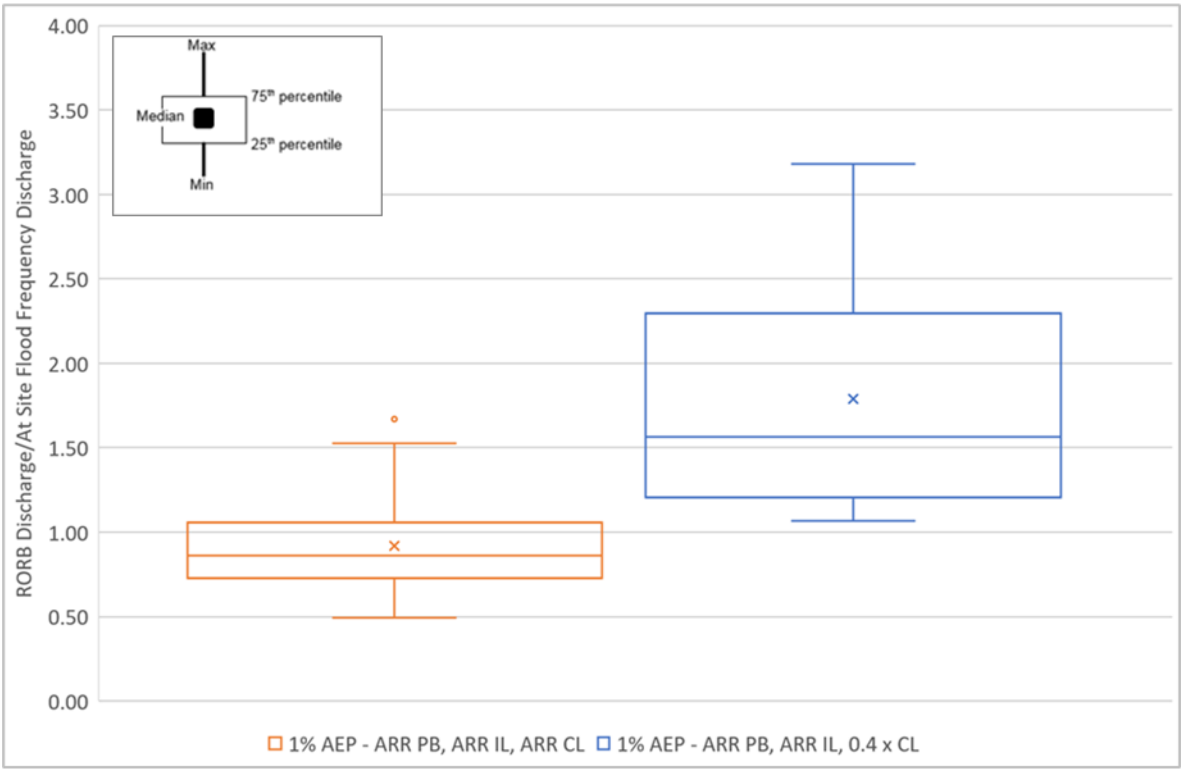


Figure 8-2: 1% AEP peak flow ratio standard ARR2019 vs 0.4 CL factor

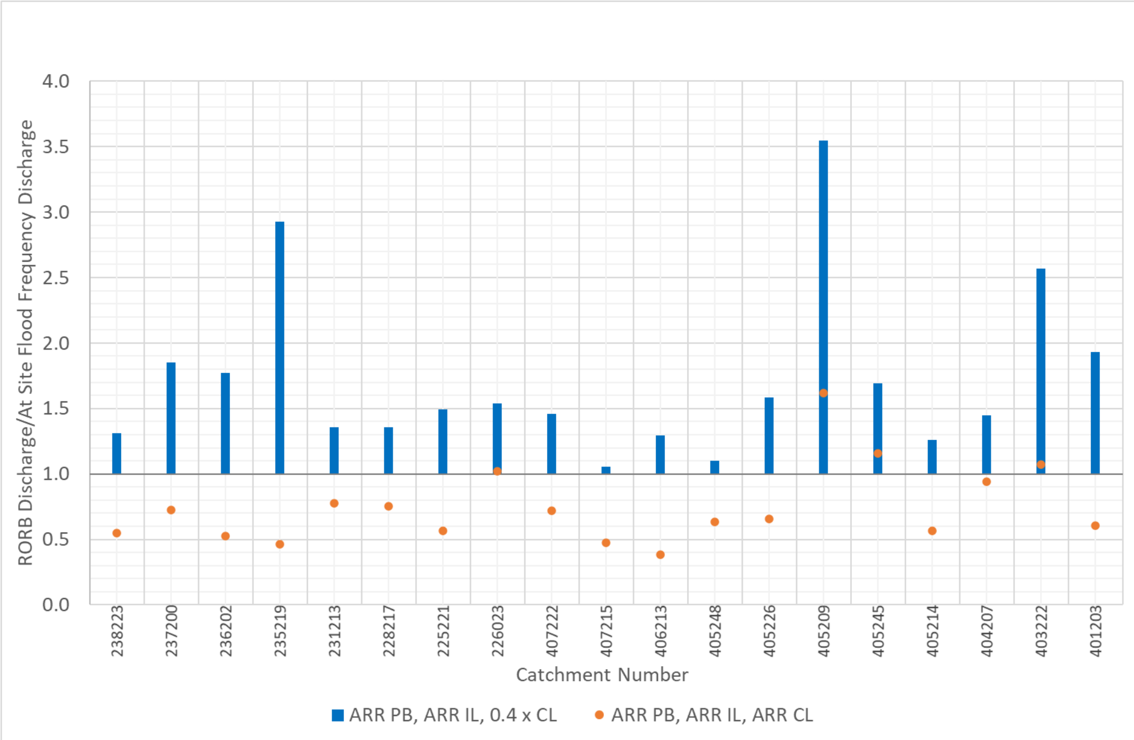


Figure 8-3: 5% AEP peak flow ratios standard ARR2019 vs 0.4 CL factor for all catchments analysed

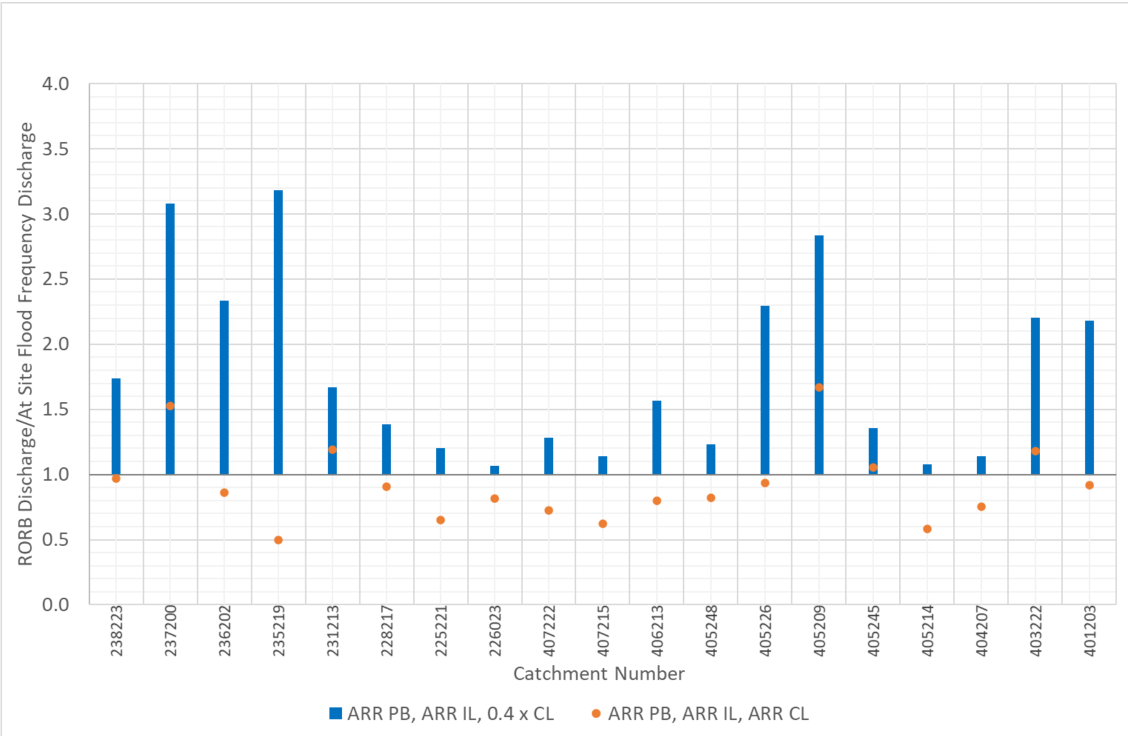


Figure 8-4: 1% AEP peak flow ratios standard ARR2019 vs 0.4 CL factor for all catchments analysed

8.2 Pre-burst rainfall magnitude

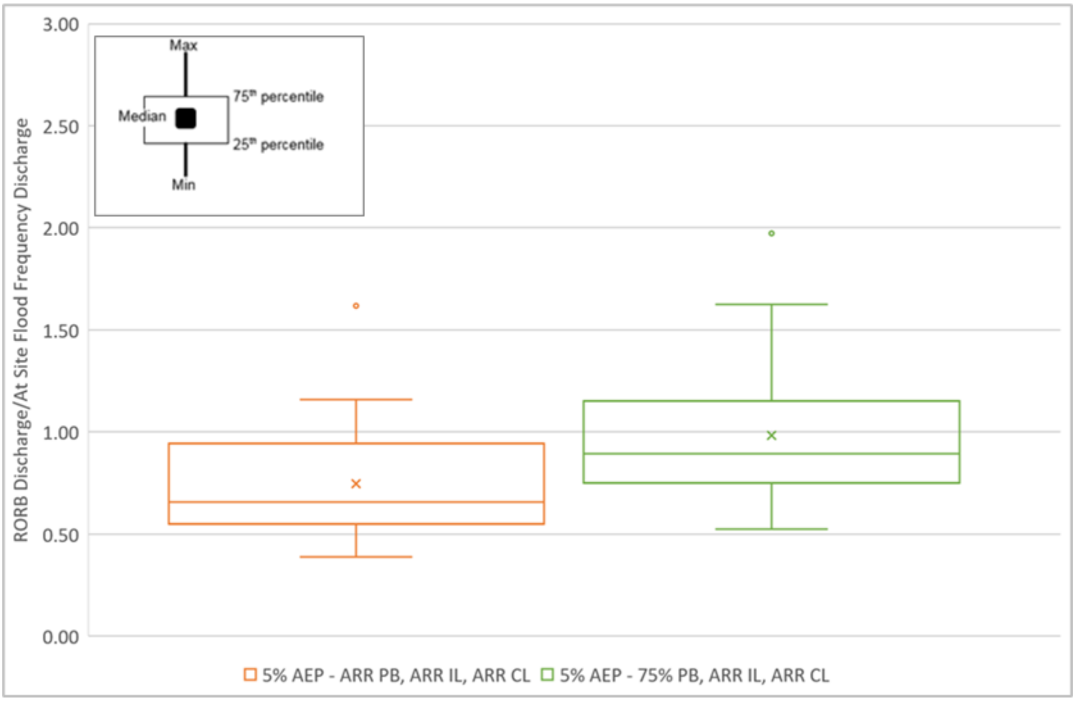
As noted in Section 6.2, it was concluded that for the catchments and AEPs analysed in this study, the modelled design flood peak flows were not sensitive to the pre-burst rainfall simulation approach adopted. However, it has been understood for some time that there is a fundamental inconsistency in the regional median initial loss values and pre-burst rainfall magnitudes provided by ARR2019.

As discussed in Section 2.4, this inconsistency is due to differing assumptions around definition of pre-burst rainfall used during the research projects underpinning pre-burst rainfall magnitudes and regional losses. As such, it was considered possible that this inconsistency could be at least partly responsible for the systemic underestimation of design flood peak flows. This assumes that the median pre-burst rainfall magnitude values are too low in comparison to the regional initial loss estimates (or vice versa), and the combination of these two inputs is then underestimating peak flow as a whole.

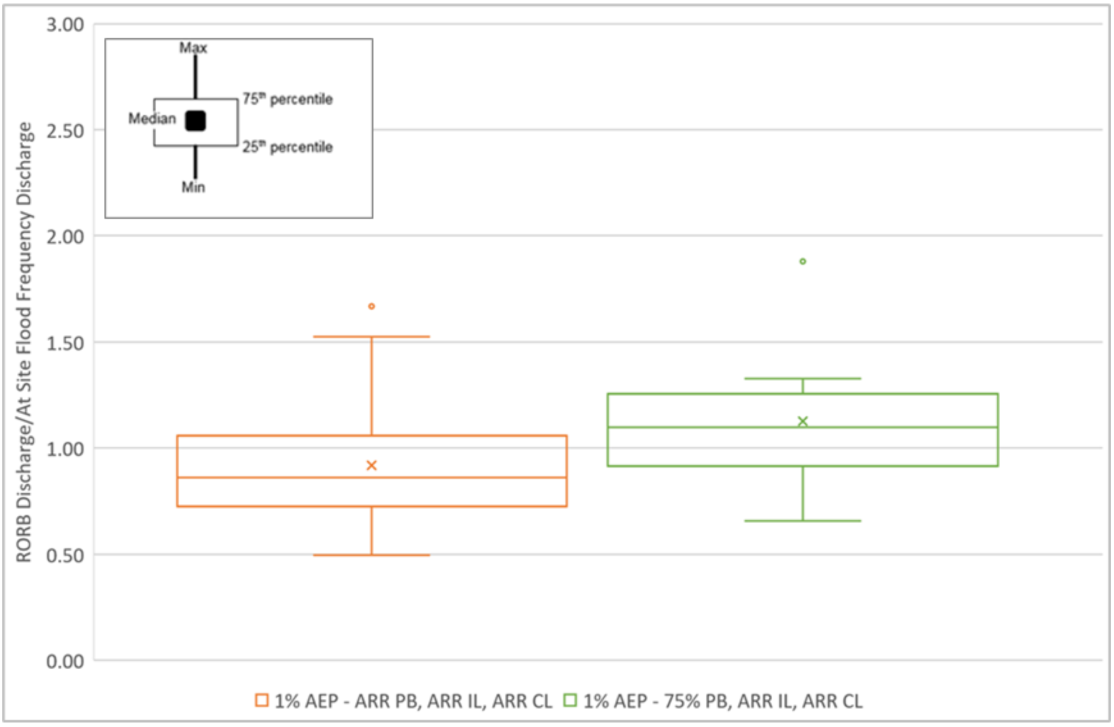
To further investigate this, modification to the adopted pre-burst rainfall magnitude was considered. This approach looked at adopting the 75th percentile ratio of pre-burst rainfall magnitude from the ARR Data Hub, instead of the median ratio values as have been used in all previous analyses.

The result of adopting the 75th percentile pre-burst rainfall magnitude estimates indicated that this approach did reduce some of the bias in design peak flow estimates for Victorian catchments. For more frequent AEPs, such as the 5% AEP, the average ratio of modelled to gauged design peak flow became very close to 1 with the median ratio for the catchments analysed sitting just below 1, as seen in Figure 8-5. Figure 8-6 also highlighted that 1% AEP average and median ratios were slightly larger than 1. This indicates a slight overestimation in design peak flow, however it removes the larger bias to underestimating flows currently present when using the standard ARR2019 values.

It should also be noted that although the average and median 1% AEP flows were slightly overestimated, the confidence limits for the 1% AEP plot were smaller than those of the standard ARR2019 outputs, indicating that the 75th percentile pre-burst rainfall magnitudes provided a better fit in general across all 19 catchments when compared to the standard ARR2019 values. The results for each individual catchment, for the 5% AEP and 1% AEP, can be seen in Figure 8-7 and Figure 8-8.



- Figure 8-5: 5% AEP peak flow ratios standard ARR2019 vs 75th percentile pre-burst



- Figure 8-6 : 1% AEP peak flow ratios standard ARR2019 vs 75th percentile pre-burst

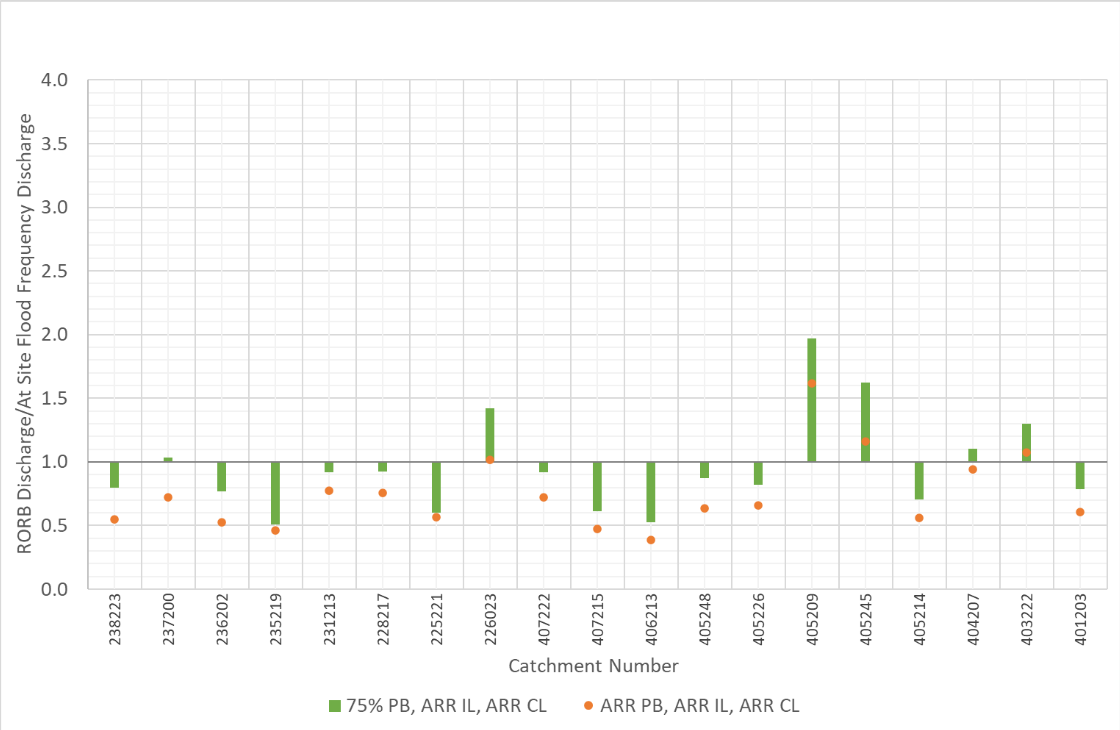


Figure 8-7: 5% AEP peak flow ratios standard ARR2019 vs 75th percentile pre-burst for all catchments analysed

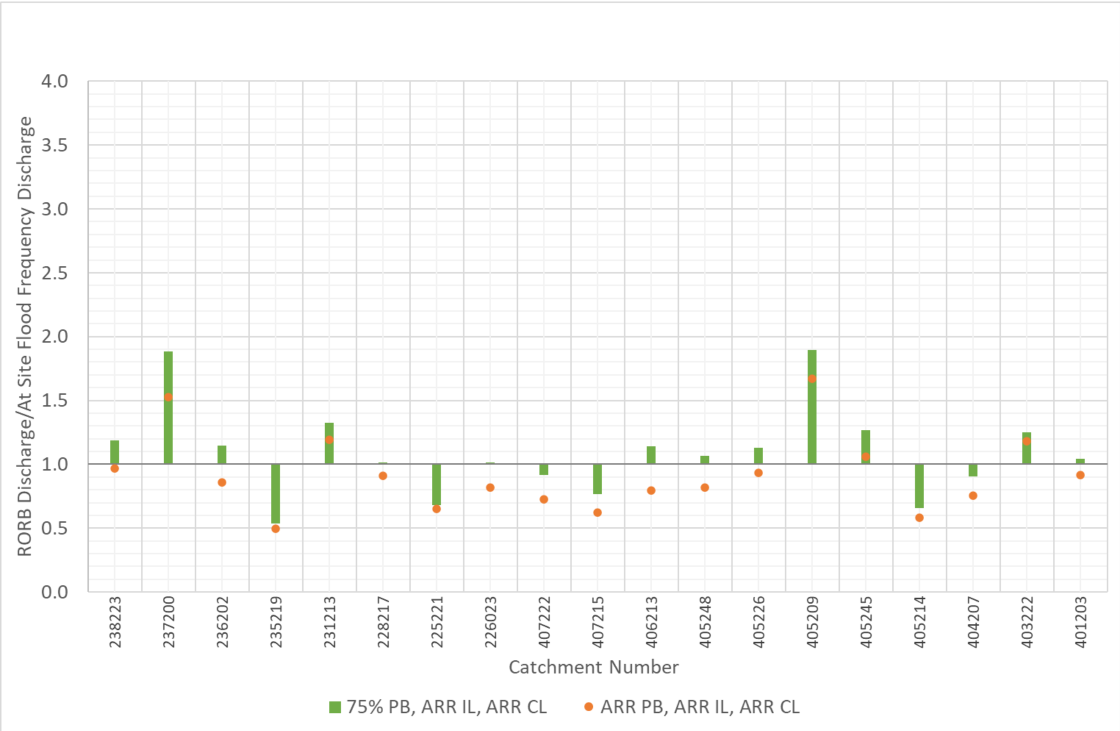


Figure 8-8: 1% AEP peak flow ratios standard ARR2019 vs 75th percentile pre-burst for all catchments analysed

8.3 Initial loss adjustment

Similar to the approach considered in Section 8.2, to account for the potential inconsistency between regional median initial loss estimates and pre-burst rainfall magnitudes, an approach was investigated to adjust the regional initial loss value. This was done instead of adjusting the pre-burst rainfall magnitude, so the adjusted initial loss values reported here were run together with median pre-burst rainfalls.

This approach considered adopting zero initial loss, instead of the regional median value provided by the Data Hub. Whilst it is conceptually problematic, trial of zero initial loss was considered a reasonable outer envelope of the potential adjustments to initial loss values. It was therefore trialled to determine whether some adjustment to initial loss might perform better than an adjustment to pre-burst rainfall magnitude.

The result of adopting zero initial loss indicated that this approach tends to overestimate design peak flow in both the average and median values for the catchments. This can be seen in Figure 8-9 and Figure 8-10. Figure 8-10 also indicated for the 1% AEP event, a larger spread of variability in results compared to standard ARR2019 approach. The results for each individual catchment, for the 5% AEP and 1% AEP, is also seen in Figure 8-11 and Figure 8-12.

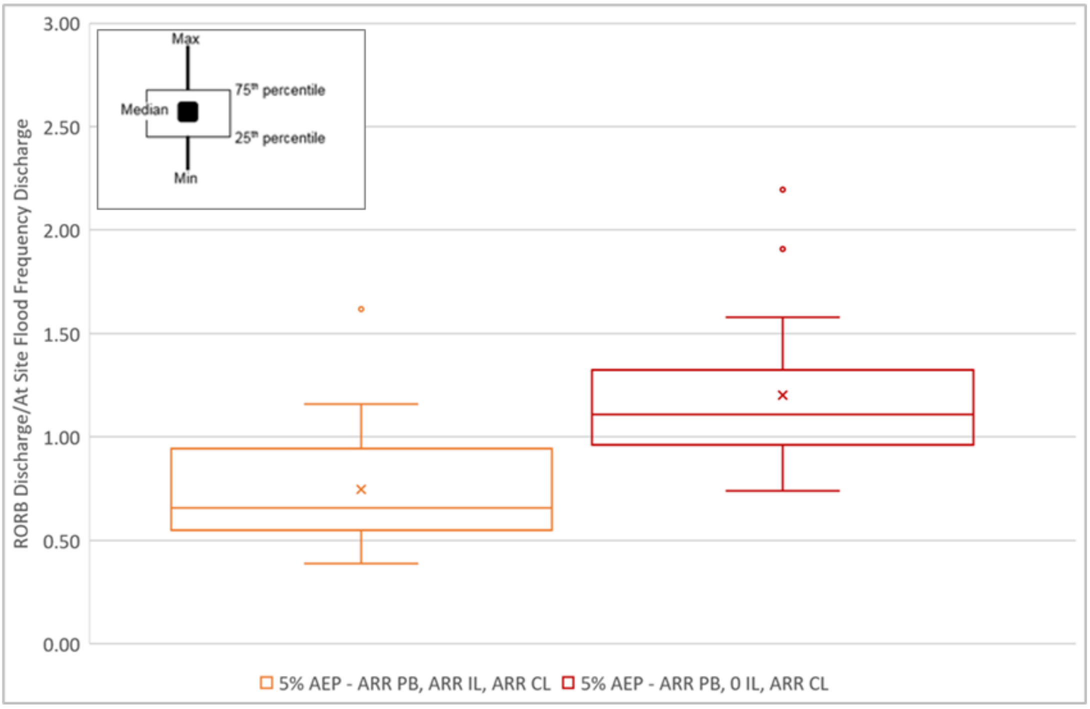


Figure 8-9: 5% AEP peak flow ratios standard ARR2019 vs zero IL

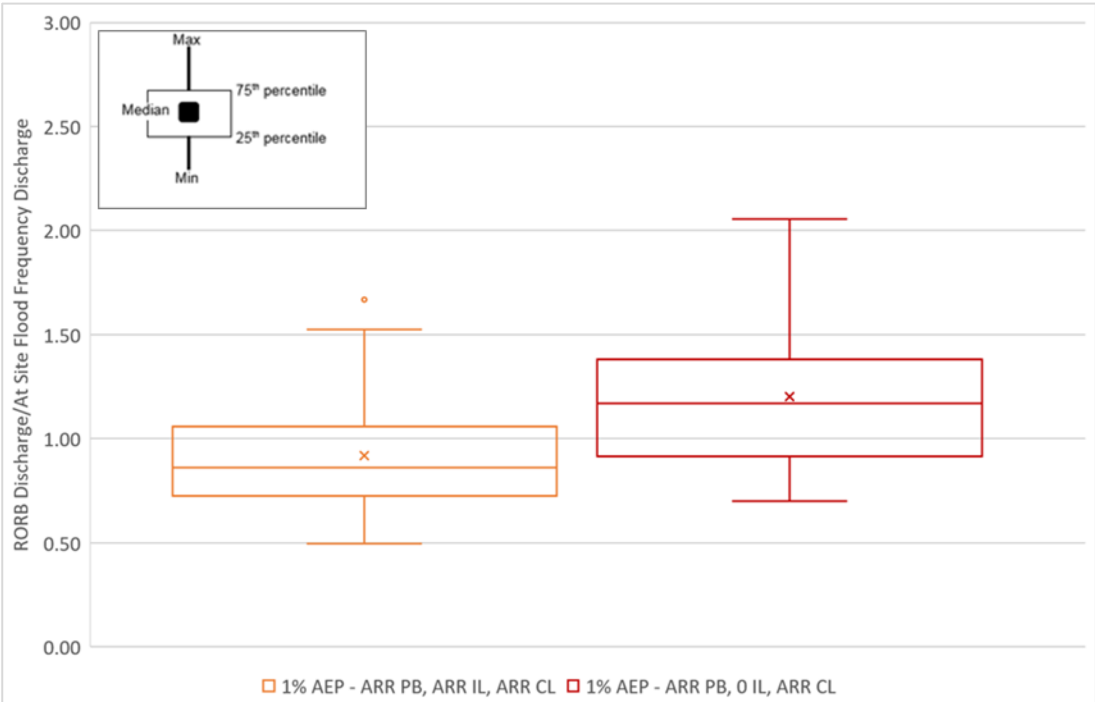
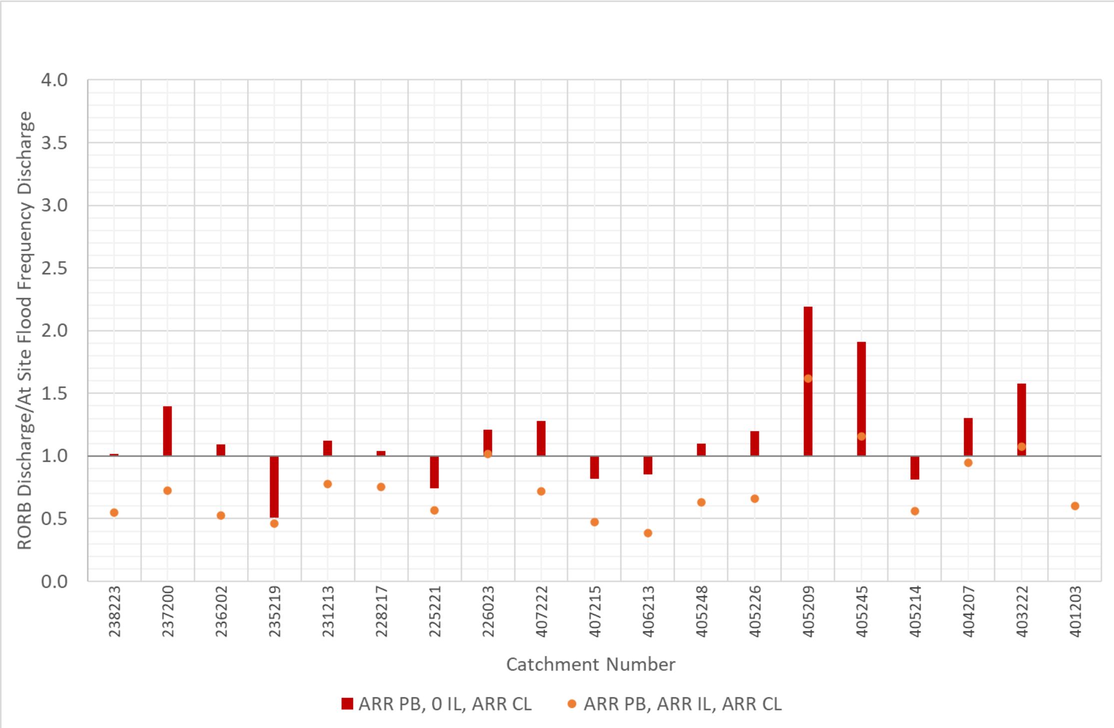
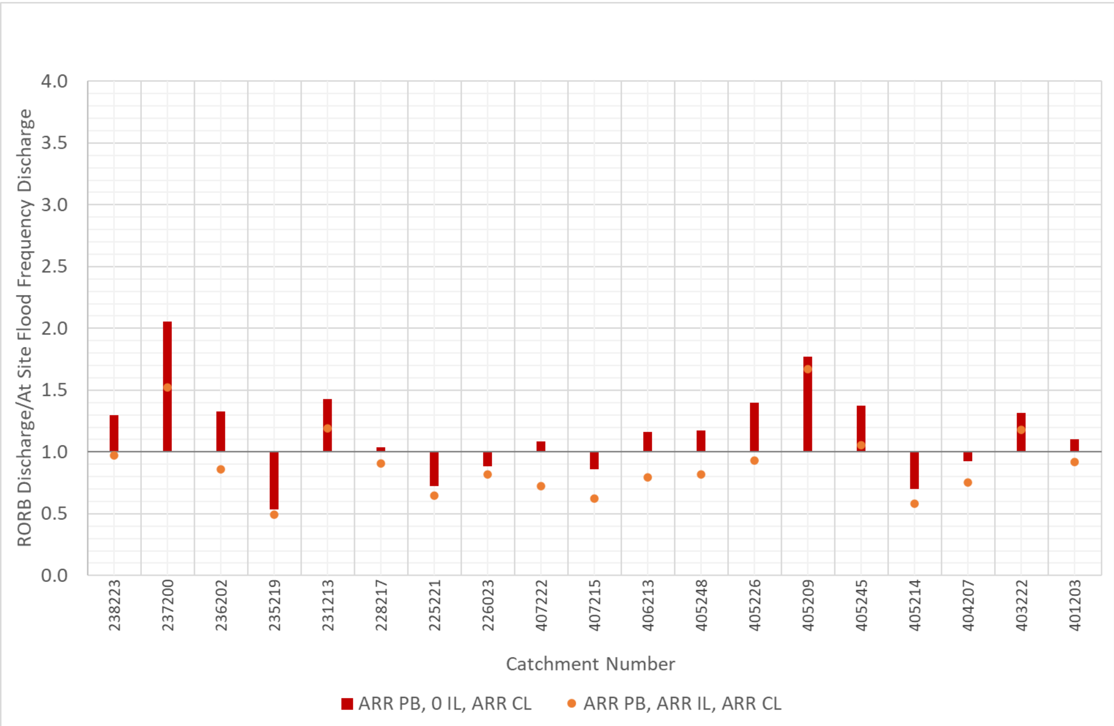


Figure 8-10: 1% AEP peak flow ratios standard ARR2019 vs zero IL



- **Figure 8-11: 5% AEP peak flow ratios standard ARR2019 vs zero IL for all catchments analysed**



- **Figure 8-12: 1% AEP peak flow ratios standard ARR2019 vs zero IL for all catchments analysed**

8.4 Summary of potential bias correction approaches

This section discusses a preliminary analysis of three broad approaches to potential bias correction for design flood estimates for Victorian catchments. The options considered were:

- Application of a uniform adjustment factor to the ARR2019 regional continuing loss values. Whilst WMAwater (2019) reported success with this approach, and a factor of 0.4 is currently recommended for NSW catchments, it was not found to be useful for Victorian catchments. Adoption of a factor of 0.4 resulted in a significant over-correction of the bias and therefore overestimation of design flood peak flows. It is possible that a larger adjustment factor could be adopted which would mitigate this over-correction, however it was shown in Section 7.2 that there was no evidence of correlation between raw and adjusted continuing loss estimates. As such, this approach is not recommended for Victorian catchments.
- Adoption of a larger pre-burst rainfall magnitude. This approach has the conceptual advantage that it treats the potential inconsistency between ARR2019 median pre-burst rainfall magnitudes and regional median initial loss estimates. It was trialled by adopting the 75th percentile pre-burst rainfall magnitudes from the Data Hub (whilst leaving all other inputs at their standard ARR2019 values). The results showed a significant decrease in bias of the modelled design peak flows.
- Adoption of a uniform adjustment to the regional median initial loss values. This approach also conceptually treats the potential inconsistency between ARR2019 median pre-burst rainfall magnitudes and regional median initial loss estimates. It was trialled by adopting a zero initial loss value as an envelope (whilst leaving all other inputs at their standard ARR2019 values). The results showed a significant decrease in bias (moving to a slight over-correction) of the modelled design peak flows.

The analysis of the zero initial loss and 75th percentile pre-burst magnitude approaches provided two potential approaches to mitigate the underestimate of design peak flows. Figure 8-13 and Figure 8-14 compare the discharge ratios of these two approaches. These figures indicate that the 75th percentile pre-burst approach provides results closer to a ratio of one in comparison to the zero initial loss approach for most catchments.

Having said this, it must be noted that the analyses undertaken in this report should be regarded as preliminary in nature only and indicative of a potential way forward. Addressing the systemic underestimation of design peak flows for Victorian catchments warrants additional research and investigation, and it may be possible, for example, to combine some estimate of pre-burst rainfall with some initial loss adjustment factor to optimise the bias correction. Alternatively, it is possible that either the pre-burst magnitudes or the regional initial losses could be recalculated for Victoria to remove the overall bias in flood estimates.

As an interim measure, in lieu of additional research, it is recommended for Victorian catchments within the influence of loss region 3, that the 75th percentile pre-burst rainfall magnitudes be adopted for design flood estimation.

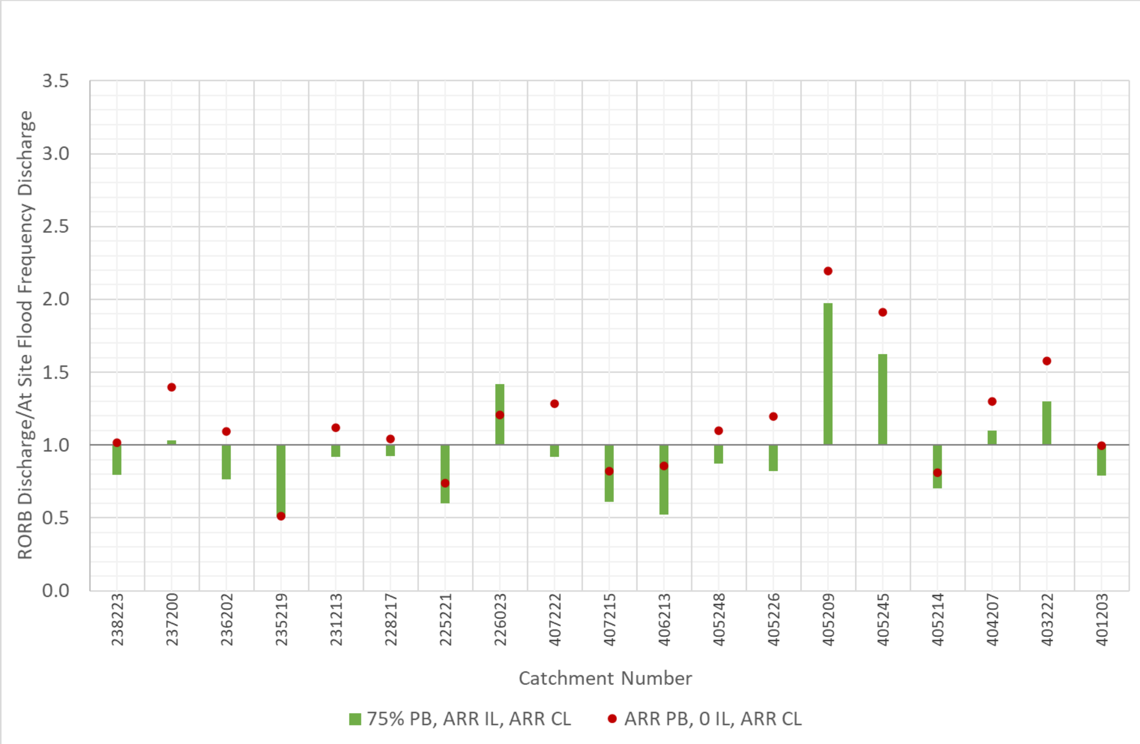


Figure 8-13: 5% AEP peak flow ratios zero initial loss vs 75th percentile pre-burst for all catchments analysed

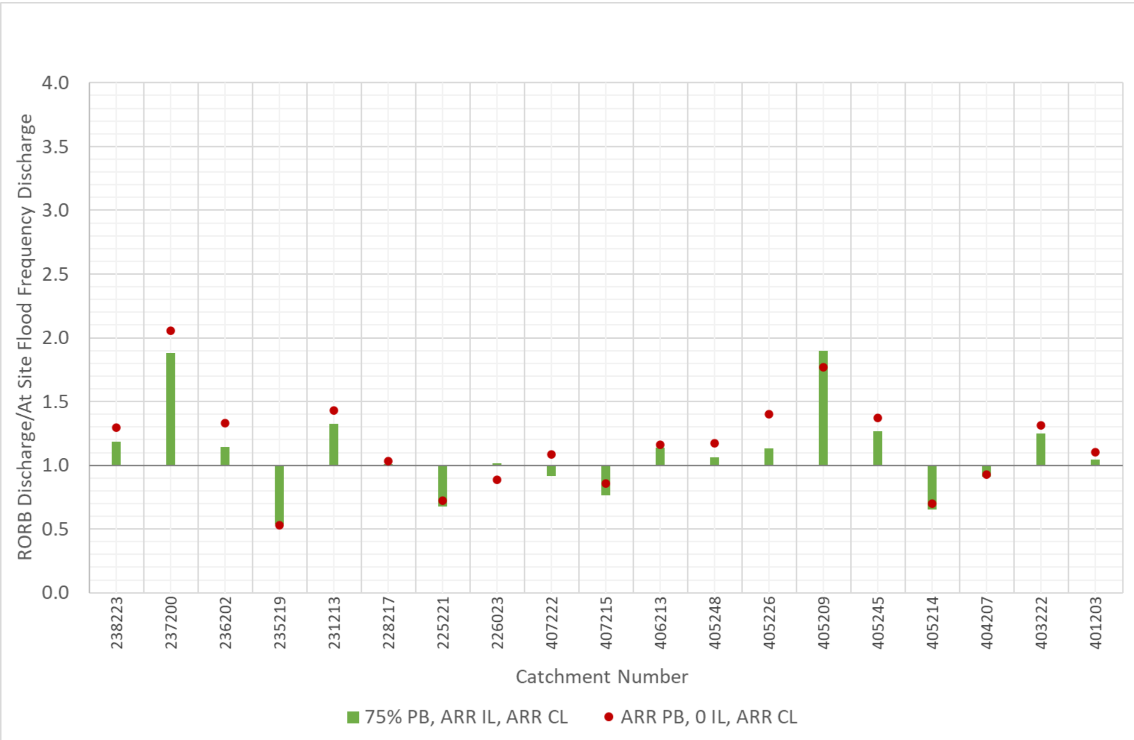


Figure 8-14: 1% AEP peak flow ratios zero initial loss vs 75th percentile pre-burst for all catchments analysed

9. Additional considerations

The outcomes of this study have focused primarily on 'typical' catchments located within loss region 3. Nevertheless, there are some key outcomes which have been identified that warrant further investigation.

9.1 Considerations for large catchments

While analysing the standard ARR2019 results, there was an indication that for catchments larger than approximately 600 km^2, the bias in flood estimates grew increasingly large. That is to say, as catchment area increases beyond this threshold, design flood peak flows are increasingly underestimated.

This can be seen in Figure 9-1 and Figure 9-2, where the ratio of modelled to gauged design flood peak flows is plotted for catchments based on their size. These figures show the ratio of modelled to gauged peak flow achieved for each catchment using both standard ARR2019 inputs as well as adopting the 75th percentile pre-burst rainfall magnitudes. Though the 75th percentile pre-burst approach does improve the overall bias, design peak flows for many of the large catchments were still underestimated.

This issue may warrant further investigation, due to the limited number of catchments available to determine if this is a trend. Conceptually speaking, it appears as though treatment of the potential inconsistency between pre-burst rainfall and regional median initial loss is less effective for larger catchments. This may be because as catchment area becomes larger, and therefore critical storm duration becomes longer, continuing loss tends to be more influential on modelled peak flow. Previous research (e.g. Lang et al, 2015) has indicated that continuing loss values should generally be adjusted as storm duration increases, to reflect the fact that over longer and longer durations continuing loss is likely to decrease as the surface soil zones of the catchment approach total saturation.

The importance of this issue may be offset by the fact that generally larger catchments within Victoria tend to be those with sufficient streamflow gauge data. Availability of gauged data would enable an at-site flood frequency analysis to be undertaken and so the adopted continuing loss value could be adjusted to reconcile the modelled and gauged design peak flow estimates.

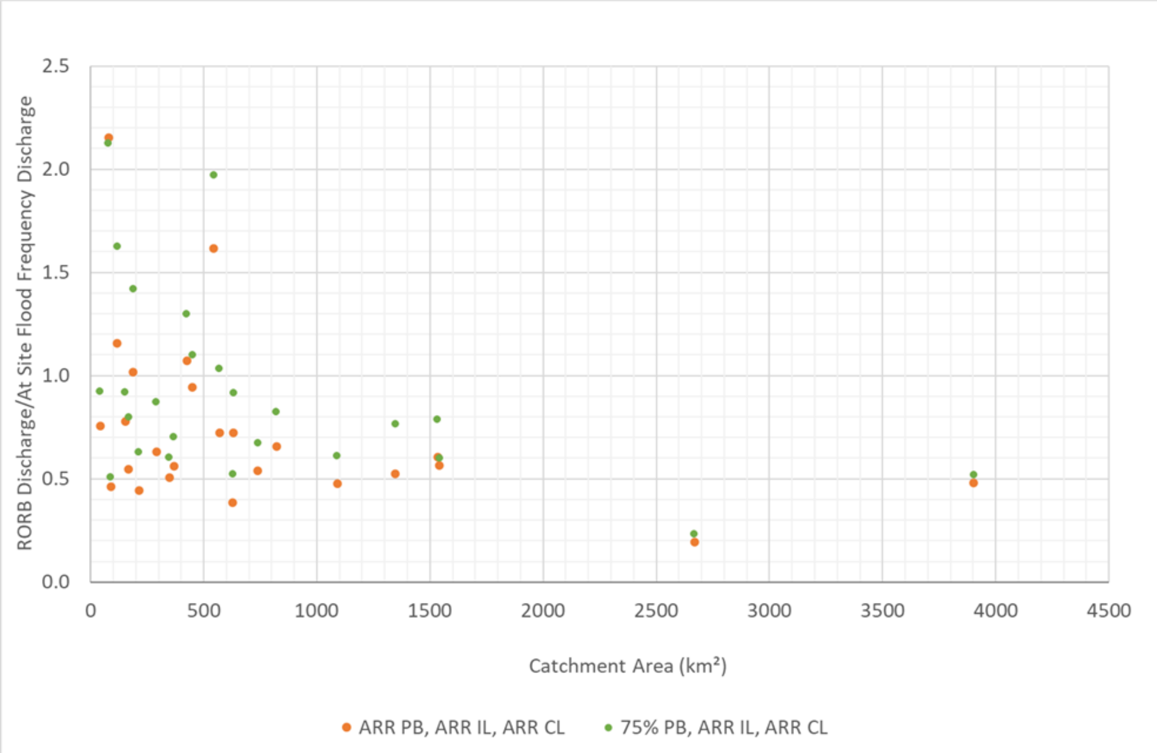


Figure 9-1: 5% AEP peak flow ratios 75th percentile pre-burst vs standard ARR2019 for all catchments analysed

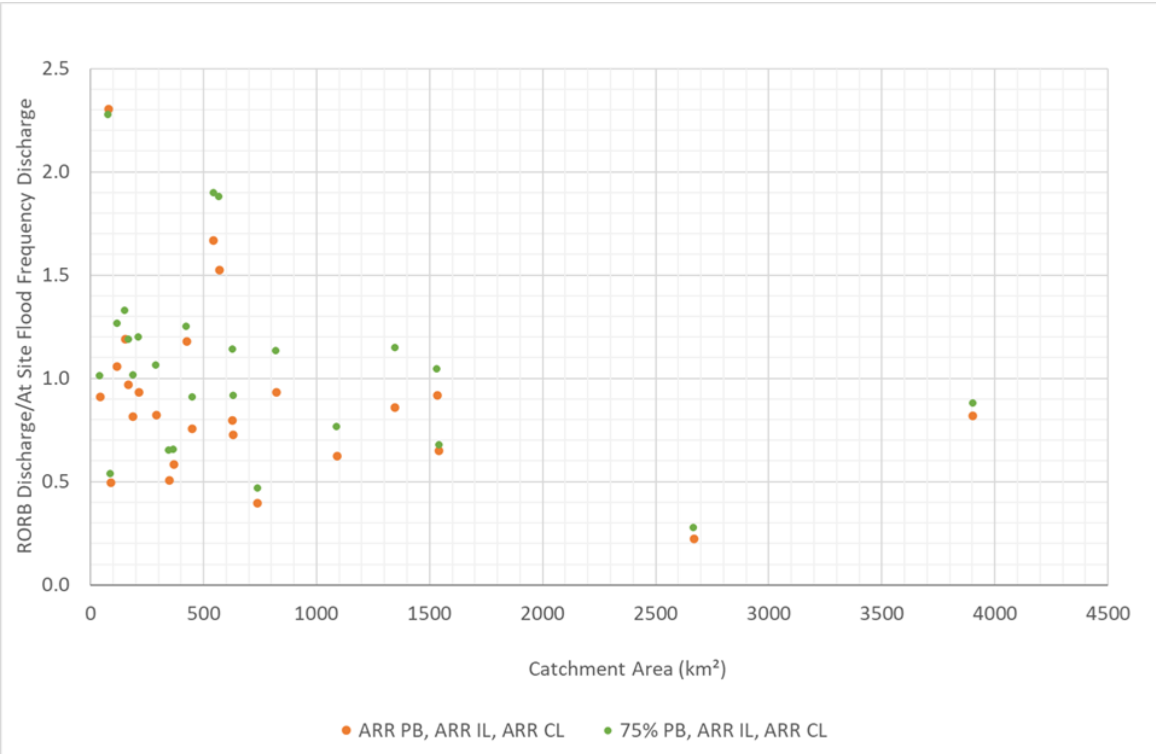


Figure 9-2: 1% AEP peak flow ratios 75th percentile pre-burst vs standard ARR2019 for all catchments analysed

9.2 Other loss regions

The outcome of the analysis indicated that adoption of the 75th percentile pre-burst rainfall magnitudes for Victorian catchments within loss region 3 was a reasonable interim approach to partly mitigate bias in modelled design flood estimates. During the course of the analysis, it was found that those catchments which overlapped loss regions, or were close to the boundary of loss regions where smoothing of the loss values had occurred, tended to produce anomalous results. In several cases, the standard ARR2019 inputs produced design flood estimates which were substantially higher than those estimated from gauged data.

As such, those catchments which were affected by other loss regions were excluded from analysis and therefore the conclusions of this report only apply to those catchments wholly within region three. With reference to Figure 6-7, loss region 3 covers the majority of Victoria, with the remainder covered by loss region 2. There are very small areas of loss region 4 in the state, and no areas classified as loss region 1. The outcomes of this study therefore apply to a majority of Victorian catchments.

Notwithstanding this, further benchmarking research into catchments in other loss regions is urgently required. This research probably cannot be conducted in a similar manner to the current study, as there are unlikely to be sufficient appropriate gauged Victorian catchments which are wholly within loss region 2. It is noteworthy that absolute loss values in region 2 are significantly lower than those in region 3, as can be seen in Figure 6-8. In particular, there is an area of western Melbourne, extending down to Geelong, where the regional continuing loss estimate is less than 1 mm/h.

Given this, there may be some value in further research associated with rederiving the regional loss estimates for all of Victoria using only the regional 3 prediction equations. This could be coupled with searching for additional gauged catchments within or close to region 2 which could be added into the analysis.

10. Recommended further work

The outcomes of this study have provided interim advice for addressing bias in design flood estimates derived using ARR2019 inputs for Victorian catchments. However, there are a number of areas where the need for additional analyses and investigations are warranted. These are described here:

- *Expand the number of catchments used for benchmarking*. Currently a total of 25 catchments have been selected and incorporated into the benchmarking process. The statistical defensibility of the results obtained would be improved if additional catchments were added, noting that this may involve additional modelling. Where possible, additional catchments in the greater Melbourne region would be desirable, as well as some catchments which are wholly or partially covered by loss region 2.
- *Review high flow rating curves for benchmarking catchments* – The benchmarking relies upon reliable estimates of recorded streamflow for each catchment. It would be desirable to undertake hydraulic modelling at the gauging stations for each of the benchmarking catchments to confirm the high flow rating.
- *Implications of adopting 75^{th} percentile pre-burst* - Further research is required to confirm the interim conclusion that bias in the derived flood estimates can be addressed by adopting the 75^{th} percentile pre-burst rainfall magnitudes in lieu of the median pre-burst data. This would ideally involve benchmarking of additional catchments as well as further investigation into the efficacy of some combination of initial loss adjustment factors along with increased pre-burst magnitudes.
- *Boundary issues between loss regions* - The boundary issues between loss regions require further investigation. This issue is critical as much of the western Melbourne region is covered by loss region 2, and the predicted regional loss values there appear anomalously low. It would be of great interest to derive losses for all of Victoria using the region 3 prediction equations and then test those catchments which lie on or near the boundary interface with these region 3 loss estimates. This may result in a significant change to guidance on losses for Victoria.
- *Reduction of continuing loss for large catchments* – From consideration of the physical processes contributing to CL it would be expected that infiltration rate and hence CL should reduce with the duration of the event. This benchmarking has shown a slight bias for flood estimates to be underestimated for larger catchments and therefore it is recommended that alternate loss models or adjustments to CL be investigated to address this issue.

Although not directly outcomes of this study, the following additional recommendations are also noted:

- *Pre-burst data for durations shorter than 1 hour*. Pre-burst values are currently not provided by ARR2019 for storm durations shorter than one hour. Further research and analysis of recorded rainfall data is required to determine whether meaningful pre-burst estimates can be derived for these very short durations. It is to be noted that this is a national need rather than specific to Victoria.
- *Benchmarking of RFFE* - Although not extensively considered as part of this study, there is anecdotal evidence of localised issues associated with the Regional Flood Frequency

Estimation (RFFE) tool. It would be of considerable value for a Victorian focused study to be commissioned which looked at benchmarking RFFE estimates to gauged and modelled data to firstly determine whether these concerns are justified.

- *Hydrologic/hydraulic model interface*. There is a national need for further research into treatment of variability across the hydrologic/hydraulic model interface. Specifically, studies are warranted which compare and contrast design peak water level estimates derived from representative hydrograph vs full ensemble/Monte Carlo approaches. This issue is particularly relevant where flood mapping is undertaken on a catchment scale.

11. Summary and Conclusions

The release of ARR2019 provided a range of new techniques and datasets to support design flood estimation in Australia. Whilst considerable effort was expended in developing the new guidance, there was limited opportunity for benchmarking the design flood estimated produced using these new datasets. As such, Melbourne Water and the Victorian Government commissioned a benchmarking study to assess whether there was systematic bias in design flood estimates for Victorian catchments using the ARR2019 techniques and data sets.

A total of 25 catchments were identified across Victoria with calibrated RORB models and a relatively reliable record of streamflow data. Modelled design flood peak flow estimates for AEPs between 10% and 1% were produced using the RORB models combined with standard ARR2019 design inputs. These results were compared to gauged design flood estimates from at-site flood frequency analysis, and it was found that the modelled peak flow values systematically underestimated the gauged values.

As such, it can be concluded that use of the standard ARR2019 design inputs for Victoria is likely to result in an underestimate of design flood peak flow in the majority of catchments.

This project also tested the variability in flood estimates resulting from three different applications of pre-burst rainfall. The applications considered the adoption of:

- Pre-burst ratios from ARR2019 (holding the 1% AEP ratio constant for all rarer events) combined with pre-burst temporal patterns.
- Pre-burst depths from ARR2019 (holding the 1% AEP burst depth constant for all rarer events), applied as an adjustment to the initial loss value.
- Pre-burst ratios from Minty and Meighan (1999) and Jordan et al. (2005) combined with pre-burst temporal patterns.

The results indicated that up to the 1% AEP, the modelled peak flow quantiles were largely invariant to the pre-burst method adopted. Conceptually, use of a pre-burst ratio rather than absolute depth approach is preferred, particularly when the focus of the study is on AEPs rarer than 1%.

Where possible, reconciliation to gauged data is the preferred approach to estimating losses. However, when reconciliation to gauged data is not possible, a preliminary investigation was undertaken for three broad approaches to potential bias correction for design flood estimates for Victorian catchments. The options considered were:

- Application of a uniform adjustment factor to the ARR2019 regional continuing loss values.
- Adoption of a larger pre-burst rainfall magnitude.
- Adoption of a uniform adjustment to the regional median initial loss values.

The results of these preliminary investigations indicate that use of the 75th percentile pre-burst rainfall magnitude data (in lieu of median pre-burst rainfall) provides results with significantly less bias than using standard ARR2019 inputs.

Notwithstanding this, it must be noted that the analyses undertaken in this report should be regarded as preliminary in nature only and indicative of a potential way forward. Addressing the systemic underestimation of design peak flows for Victorian catchments warrants additional research and investigation, and it may be possible, for example, to combine some estimate of pre-burst rainfall with some initial loss adjustment factor to optimise the bias correction. Alternatively, it is possible that either the pre-burst magnitudes or the regional initial losses could be recalculated for Victoria to remove the overall bias in flood estimates.

As an interim measure, in lieu of additional research, it is recommended for Victorian catchments within the influence of region 3 losses, that the 75th percentile pre-burst rainfall magnitudes be adopted for design flood estimation along with Data Hub values of initial and continuing loss.

In line with AR2019 recommendations (Section 3.3.3 of Book 5; Section 5 of Book 7), it is stressed that flood estimates are best derived using information local to the specific catchment of interest. A variety of approaches are available, and loss estimates can be obtained by one or more of the following approaches:

1. *Reconciliation with at-site flood frequency quantiles*: initial and continuing losses are varied within their expected range to achieve a reasonable level of agreement between estimates derived from rainfall-based modelling and flood frequency analysis.

2. *Reconciliation using within-catchment transposed flood quantiles:* streamflow observations are commonly available at gauging stations upstream or downstream of the site of interest, and flood quantiles derived from these sites can be transposed to the site of interest and used for reconciliation as described in approach 1.

3. *Event-based calibration*: continuing losses obtained from calibration of historical events provide some indication of typical design values, noting that past historical events are biased towards wet catchment conditions; initial losses from historical events are highly variable and information from a small sample of events are of low utility (and therefore some form of reconciliation with other sources of information is recommended).

4. *Reconciliation using nearby catchment transposed flood quantiles:* regional flood quantiles derived using RFFE and other procedures (Section 3, Book 3, ARR2019) can be used for reconciliation as described in approach 1.

5. *Transposition of losses*: initial and continuing loss estimates validated on nearby catchments which are considered to be hydrologically similar.

6. *Regional losses (ARR Data Hub)*: unmodified initial and continuing loss estimates obtained from the Data Hub losses can be adopted in data poor areas, noting that in loss region 3 these should be combined with 75th percentile pre-burst values.

The above methods are listed in notional order of defensibility, where the first approach is the most preferred and the sixth method is the least preferred. However, for any given catchment the defensibility of the adopted approach varies with the relevance of the available data, where it is commonly necessary to make assumptions about how estimates might vary with catchment size, event severity, and the hydrologic similarity of catchment conditions. It is thus recommended that more than one approach be applied and that careful judgement be used to derive a single set of best estimates.

12. References

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) (2019) Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia (Geoscience Australia), Australia.

Frost, A., Ramchurn, A., Hafeez, M., Zhao, F., Haverd, V., Beringer, J., & Briggs, P. (2015). Evaluation of AWRA-L: the Australian Water Resource Assessment model. Modsim 2015 - 21st International Congress on Modelling and Simulation, 29 November - 4 December 2015, Gold Coast, 0, 2047–2053.

Gallant JC, Dowling TI, Read AM, Wilson N, Tickle P and Inskeep C (2011), 1 second SRTM Derived Digital Elevation Models User Guide. Geoscience Australia, <http://www.ga.gov.au/topographic-mapping/digital-elevation-data.html>.

Haddad, K., Rahman, A., Weinmann, P. E., Kuczera, G. A., & Ball, J. (2010). Streamflow data preparation for regional flood frequency analysis: lessons from southeast Australia. Australian Journal of Water Resources, 14(1), 17–31.

Hill, P.I., Graszkiewicz, Z., Taylor, M. and Nathan, R.J. (2014), *Loss Models for Catchment Simulation*. Australian Rainfall and Runoff Revision Project 6: Phase 4 Analysis of Rural Catchments, ARR Report Number P6/S3/016B, ISBN 978-085825-9775.

Hill, P.I., Graszkiewicz, Z., Loveridge, M., Nathan, R.J., Scorah, M. (2015) Analysis of loss values for Australian rural catchments to underpin ARR guidance. Hydrology and Water Resources Symposium 2015. Hobart. 9-10 December 2015.

Hill, P.I., Nathan, R.J., Zhang, J. (2016) Application of AWRA-L gridded soil moisture data for flood estimation. 37th Australian Hydrology and Water Resources Symposium. 28 Nov – 2 December Queenstown New Zealand.

Hill, P.I. Thomson, R. (2019) Chapter 3 - Losses of Book 5 - Flood Hydrograph Estimation in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia, © Commonwealth of Australia (Geoscience Australia)

Hill, P., Mein, R., & Maheepala, U. (1996). *Empirical analysis of data to derive losses: methodology, programs and results.* Australia

Hosking, J. R., & Wallis, J. R. (1997). *Regional Frequency Analysis: An Approach Based on L-Moments*. Cambridge University Press.

Jordan, P.W., Nathan, R.J., Mittiga, L. and Taylor, B. (2005), *Growth curves and temporal patterns of short duration design storms for extreme events*. Australian Journal of Water Resources, Vol. 9, No. 1, pp 69-80.

Jordan, P., Nathan, R., Podger, S., Babister, M., Stensmyr, P., Green, J. (2016), *Areal Reduction Factors*, Chapter 4 of Book 2 in Australian Rainfall and Runoff – A Guide to Flood Estimation. The Institution of Engineers, Australia, Barton, ACT.

Kuczera, G., & Franks, S. (2019). *At-Site Flood Frequency Analysis*, Chapter 2, Book 3. In J. Ball, M. Babister, R. Nathan, W. Weeks, E. Weinmann, M. Retallick, & I. Testoni (Eds.), Australian Rainfall and Runoff: A Guide to Flood Estimation. Commonwealth of Australia.

Ladson, A., Brown, R., Neal, B., & Nathan, R. (2013). *A standard approach to baseflow separation using the Lyne and Hollick filter*. Australia Journal of Water Resources, 17(1), 25–33.

Lang, S.M., Hill, P.I. Scorah, M., Stephens, D.A. (2015) Defining and calculating continuing loss for flood estimation. 2015 Hydrology and Water Resources Symposium. Hobart. 9-10 December 2015.Laurenson, E.M., Mein, R and Nathan, R.J. (2010), RORB Version 6 Runoff Routing Program: User Manual, Australia, Melbourne, VIC.

Lyne, V., Hollick, M. (1975), *Stochastic Time-Variable Rainfall-Runoff Modelling,* Institute of Engineers Australia National Conference, pp 89-93.

Minty, L.J and Meighen, J. and. (1999), *Rainfall Antecedent to Large and Extreme Rainfall Bursts over Southeast Australia*. Hydrometeorological Advisory Service, Bureau of Meteorology, Commonwealth of Australia. HRS Report No. 6

Nathan, R. (2003). *Use of Monte Carlo simulation to estimate the expected probability of large to extreme floods*. 28th International Hydrology and Water Resources Symposium.

Nathan, R., Stephens, D., Smith, M., Jordan, P., Scorah, M., Shepherd, D., Hill, P. and Syme, B.(2016) *Impact of natural variability on design flood flows and levels* in 37th Hydrology & Water Resources Symposium.

Nathan, R., Weinmann, E., & Hill, P. (2002). *Use Of A Monte Carlo Framework To Characterise Hydrological Risk*. ANCOLD Bulletin, 122(Civ), 55–64.

Nathan, R.J. and Weinmann, P.E. (2016), *Estimation of Very Rare to Extreme Floods*, Book 8 in Australian Rainfall and Runoff – A Guide to Flood Estimation. The Institution of Engineers, Australia, Barton, ACT.

Pearse, M., Jordan, P., Collins, Y. (2002), A simple method for estimating RORB model parameters for ungauged rural catchments, 27th IEAust Hydrology and Water Resources Symposium, Melbourne, 2002.

Rahman, A., Haddad, K., Kuczera, G., & Weinmann, E. (2019). *Regional Flood Methods*, Chapter 3, Book 3. In J. Ball, M. Babister, R. Nathan, W. Weeks, E. Weinmann, M. Retallick, & I. Testoni (Eds.), Australian Rainfall and Runoff: A Guide to Flood Estimation2. Commonwealth of Australia.

Scorah, M., Hill, P., Nathan, R., Graszkiewicz, Z.,(2015). Outcomes from a pilot study to investigate pre-burst rainfall depths for Australian catchments. Proceedings of the 2015 Hydrology and Water Resources Symposium, 7 – 10 December, Hobart

Scorah, M., Hill, P., Lang, S. and Nathan, R. (2016), *Addressing embedded bursts in design storms for flood hydrology*. Proceedings of the 37th Hydrology and Water Resources Symposium, Queenstown, New Zealand.

Scorah, M., Stephens, D., & Nathan, R. (2018). *Benchmarking the selection of probability neutral hydrologic design floods for use in 2D hydraulic models*. 39th Australian Hydrology and Water Resources Symposium. Melbourne, 3rd-6th December,2018, 749–761

WMAWater. (2019), *Review of ARR Design Inputs for NSW*. Office of Environment and Heritage, NSW, Australia.

Appendix A Review of ARR2019 Pre-burst Data

Australian Rainfall and Runoff

Pre-burst rainfall

Final

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May 2020

Document control

Version	Date	Distribution	File
Draft A	27 Apr 2020	HARC	N621_Preburst_Ap0
Draft B	4 May 2020	HARC, Rory Nathan	N621_Preburst_Bp0
Draft C	22 May 2020	HARC, Rory Nathan	N621_Preburst_Cp0
Final 1	19 Aug 2020	HARC	N621_Preburst_F1

Cover photo: Floodplain of the Murrumbidgee River at Gundagai

Summary

This report discusses pre-burst rainfall and how it is used in hydrologic modelling. It:

- highlights the shortcomings of the currently available pre-burst data and guidance provided in Australian Rainfall and Runoff 2019
- identifies issues for practitioners
- outlines the work required to develop better data and methods.

There are several limitations and uncertainties associated with the pre-burst values provided by ARR 2019. These make it challenging for practitioners to have confidence in the data and suggests that more work is required to finalise the pre-burst values and provide consistent advice on their use.

Particular issues relate to:

- Lack of verification

  The report on pre-burst analysis was never finalised, verified or publicly released.

- Reliance on outdated IFD data

  Estimates of burst severity are based on the now superseded 2013 IFD values and should be updated to use the 2016 IFD estimates.

- The use of a critical burst approach to determine pre-burst rainfall depth

  There is an acknowledgment in ARR that this approach may result in pre-burst values being biased low. Alternative approaches are available.

- Limited range of durations

  Pre-burst data is only available for durations from 60 to 4320 min (1 to 72 hours). This is a particular problem for modelling of small urban catchments where storm durations less than 60 min are often important. Practitioners are forced to extrapolate to shorter durations with little guidance, resulting in inconsistent approaches. This report recommends a procedure to derive short duration pre-burst values.

- Limited range of AEPs

  Pre-burst data is available for AEPs from 50% to 1%. This is insufficient for many modelling applications. When using Monte Carlo modelling approaches, it is likely that pre-bursts out to 1 in 2000 AEP will be required. By necessity, practitioners are developing their own procedures. There is also a lack of guidance on the best way to sample from pre-burst distributions.

- Limited guidance on modelling approaches using pre-burst rainfall

  ARR does not provide clear advice on how pre-burst should be used in modelling, in particular, whether a complete storm, or a burst approach should be used.

- Limited guidance on pre-burst temporal patterns

  If a complete storm approach is to be used for modelling, then temporal patterns are required for the pre-burst rainfall. The only guidance in ARR related to pre-burst patterns is in Book 8, for very rare to extreme floods. For more frequent rainfalls, practitioners have adopted pragmatic approaches but these are largely untested.

- Limited guidance on estimating burst initial loss

  Pre-burst values are required as part of the estimation of burst initial loss, however at least four approaches have been proposed but there is limited guidance on their application. The different methods result in large variation in loss estimates.

- Lack of benchmarking

  To date there has been limited benchmarking of the ARR recommended inputs, including pre-burst, to ensure that design flood estimates are reasonable. Where benchmarking has been undertaken, significant bias has been found.
- Different storm definitions used in the pre-burst and losses projects

  The ARR pre-burst and temporal pattern project (Project 3) used different event definitions to those used to derive losses (Project 6). Although the magnitude of pre-burst are similar at 4 of 5 sites that were examined, the variation with duration and AEP differs. In contrast with data hub values, Project 6 pre-burst is invariant with AEP and there is a consistent decreasing trend in pre-burst ratio with duration

The current benchmarking project will address some of these issues but more work is required, in a separate project, to provide adequate pre-burst data and guidance for practitioners. The issues highlighted here could provide the basis to scope such a project.

This review has also highlighted two issues in the way RORB handles pre-burst:

- RORB does not undertake Monte Carlo sampling of pre-burst, instead it holds pre-burst constant, at the median value for each combination of duration and AEP. This provides a higher value of burst initial loss that would be the case if the pre-burst distribution was sampled.
- RORB uses pre-burst temporal patterns which were obtained from analysis of extreme events (Minty and Meighen, 1999). It is not clear if these patterns are appropriate, especially for frequent AEPs.

Abbreviations

AEP	Annual Exceedance Probability
ARF	Areal Reduction Factor
ARR	Australian Rainfall and Runoff
ARR2019	Australian Rainfall and Runoff 2019 edition (Ball et al., 2019).
GSAM	Generalised Southern Australian Method (for estimating PMP)[1]
GSAMARP	Generalised Southern Australian Method Antecedent Rainfall Project (Minty and Meighen, 1999)
IFD	Intensity Frequency Duration
PMP	Probable Maximum Precipitation

Definitions

Critical burst	The rarest burst period (of any duration) within a complete storm

[1] For discussion of the GSAM see http://www.bom.gov.au/water/designRainfalls/pmp/gsam.shtml

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1. Introduction

This report discusses pre-burst rainfall and how it is used in hydrologic modelling. It highlights:

- the shortcomings of the currently available pre-burst data and related guidance provided in Australian Rainfall and Runoff 2019
- identifies issues for practitioners
- outlines the work required to develop better data and methods.

Pre-burst rainfall is an artefact of the way that real storms are studied to determine rainfall totals to use in hydrologic design. Intense bursts of rain within storms are analysed to provide information about the intensity, frequency and duration (IFD[2]) of rainfall at a particular location. Hydrologists use design rainfall bursts, of specified duration and exceedance probability, as a key input to determine design flood events.

Often, the rainfall bursts used in IFD analysis are only part of a complete storm. There will be some rain before a burst, between the start of the burst and the start of the storm; this is referred to as 'pre-burst' rainfall. There can also be post-burst rainfall although this is usually ignored.

When it comes to hydrologic design, the pre-burst rainfall needs to be accounted for in some way. A critical aspect of this is the desire for 'probability neutrality'. That is, when modelling, the design rainfall of some exceedance probability, should lead to a flood of the same probability. The correct amount of pre-burst rainfall must be identified to maintain probability neutrality.

1.1. Relationship between pre-burst rainfall and catchment losses

Accounting for pre-burst rainfall is important because of its interaction with initial loss - the rain that falls at the start of a storm which is lost and does not contribute to runoff. Once initial loss is satisfied, streamflow increases and the hydrograph begins to rise.

Initial loss can be related to complete storms or rainfall bursts within storms (Figure 1):

- burst initial loss is the amount of burst rainfall that occurs before the hydrograph rise
- storm initial loss is usually larger, representing all the storm rainfall that occurs before the hydrograph rise.

Burst initial loss is usually a positive values but can be negative (when the hydrograph rise occurs before the start of the burst). If a burst occupies a complete storm then burst and storm initial loss will be equal.

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[2] IFD data is available from the Bureau of Meteorology, http://www.bom.gov.au/water/designRainfalls/revised-ifd/

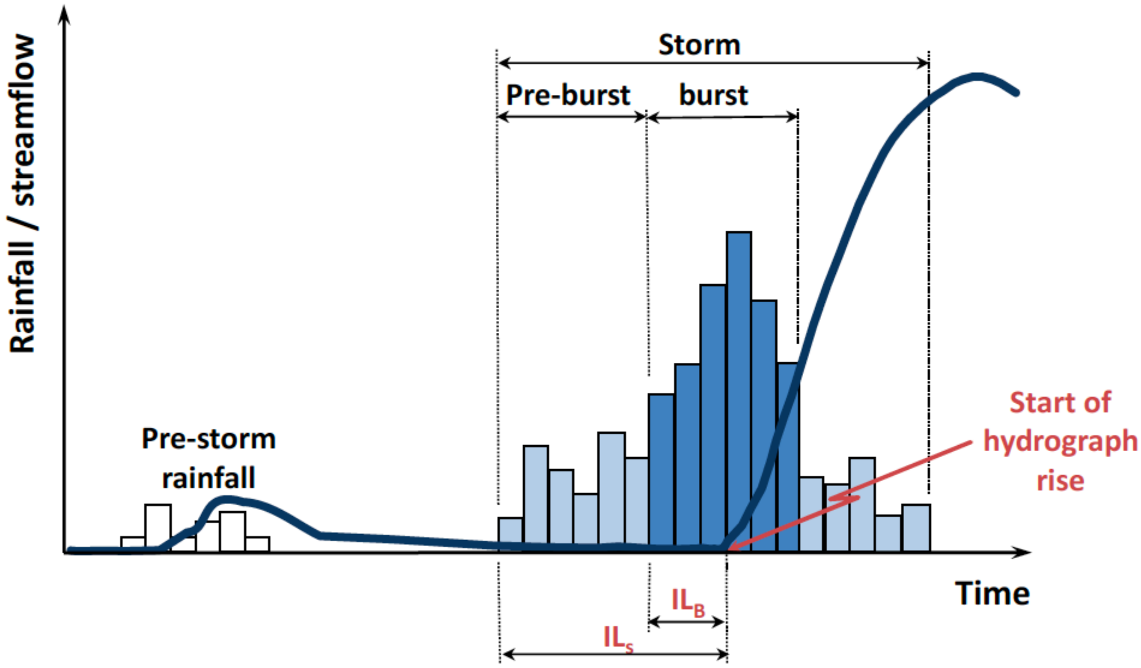

Figure 1: Burst initial loss (IL_B) and storm initial loss (IL_S) (Hill et al., 2014)

Figure 1 suggests a relationship between:

- burst initial loss (IL_b),
- storm initial loss (IL_s) and
- pre-burst rainfall (P).

This can be stated simply, perhaps simplistically, as $IL_b = IL_s - P$

Equation 1

There are important aspects that complicate this relationship:

- The three parameters (burst and storm initial loss and pre-burst rainfall) are not constant but vary between locations and storms. Information is available on the statistical distribution of storm initial loss and pre-burst rainfall. There is no independent information available on burst initial loss; it can only be determined by difference.
- The relationship between bursts, storms and pre-burst is influenced by duration. Longer bursts usually occupy a greater portion of a storm so pre-burst rainfall decreases with burst duration and burst losses approach storm losses. Dealing with pre-burst rainfall is most important for short duration events.
- Burst loss may be negative when the hydrograph rise occurs before the start of the burst. This is most common for short duration events in rapidly responding small catchments. Physically, this means pre-burst rainfall is greater than storm initial loss and is contributing significantly to runoff. There is limited advice in ARR on how this should be handled[3].
- The pre-burst rainfall information was derived in a separate project to that used to estimate the storm initial loss data provided by the ARR[4]. Equation 1 will only "work" if the pre-burst is defined in a way that is consistent with the analysis of rainfall used to

3 ARR advice on dealing with negative IL_b is listed in Book 7 Chapter 5.5.

4 Losses were developed in ARR revision project 6 (Hill et al., 2014; 2015; 2016).

derive losses. The key issue relates to the definition of bursts and storms, particularly the start and end points. As explored below, pre-burst estimates can be sensitive to this definition.

1.2. Modelling approaches using pre-burst rainfall

The various source of information and advice in ARR has led to two main modelling approaches, neither of which is completely satisfactory.

- **Complete storm approach**
  i. Obtain a burst depth from IFD data for a given location, duration and AEP
  ii. Obtain a pre-burst depth for a given duration and AEP
  iii. Prepend the pre-burst depth to the burst depth to create a complete storm
  iv. Obtain a storm initial loss value from the data hub
  v. Use the complete storm with a storm initial loss value in modelling.

  The challenges with the complete storm approach are that:

  - There is limited information on the temporal pattern to use for pre-burst rainfall.
  - The pre-burst value may be incompatible with the storm initial loss
  - There is a lack of advice on how to sample from pre-burst rainfall if a Monte Carlo modelling approach is used.

- **Burst approach**
  i. Obtain a burst depth from IFD data for a given location, duration and AEP
  ii. Obtain a pre-burst depth for a given duration and AEP
  iii. Obtain a storm initial loss value from the data hub
  iv. Subtract the pre-burst off the storm initial loss to create a burst initial loss.
  v. Use the burst rainfall and burst initial loss in modelling.

  Challenges with the burst approach are:

  - Burst initial loss may be negative if pre-burst rainfall exceeds storm initial loss. There is limited guidance in ARR on how this should be handled.
  - As above, there is a lack of advice on how to sample from pre-burst rainfall. This has led to four different approaches to estimating burst initial loss as explored in Appendix A.

2. Australian Rainfall and Runoff Pre-burst values

Pre-burst values were derived for Australian Rainfall and Runoff as part 2 of revision project 3 Loveridge et al. (2015a; 2015b). This section reviews the derivation method and highlights limitations in the available data and guidance.

A summary of the steps used to determine pre-burst rainfall is as follows:

- Storm events were identified and stored in the national storm database

- Critical storm bursts were identified within each storm event
- The pre-burst for each storm event was calculated as the rainfall prior to the critical burst
- At each point on a rectangular grid across Australia, storms were selected to represent a range of durations and severities. Forty storms were chosen for each of 66 combination of duration and AEP.
- Pre-burst from these 40 storms was calculated and used to estimate the median pre-burst and the distribution of pre-burst.

Each of these steps is explained in more detail.

2.1. Storm definition and the national storm database

Pre-burst estimates are based on analysis of the national storm database which consists of the pluviograph record from 140,000 storms (Stensmyr et al., 2015). Information is held in an SQL database which is was created, and is held by WMA Water.

The procedure to identify storm events for incorporation in the database was as follows:

1. Choose a duration range corresponding to a standard duration (Table 1)
2. Find a candidate event by searching a pluviograph record until a burst is found that is above 1EY for that duration
3. Define the storm event surrounding that burst by iteratively refining the start and end of the event.
4. Identify the **critical burst** for the event
5. If the critical burst duration is within the critical bin range, then store the event.

The standard durations and bin ranges for critical durations are shown in Table 1.

Table 1: Standard durations and corresponding bin ranges

Standard Durations			Critical duration bin range	
Minutes	Hours	Days	Lower bound (hours)	Upper bound (hours
5			0.075	0.125
10			0.125	0.2083
15	0.25		0.2083	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	

2.2. Iterative search to find the start and end of an event

The iterative procedure is complex but can be summarised as follows. The application of this procedure is a function of the duration of interest, which is selected from the durations shown in Table 1.

1. Broadly define the start and end of the event by moving outward from the identified burst to find the rainfall that matches the first criteria; which is, the first 24 hour period with rainfall below 10 mm.
2. Move outward from where the first criteria ends to find the first period that matches the second criteria; which is, the first period based on the chosen duration where rainfall is below the specified threshold (from 1 mm to 4 mm depending on duration). The period, depends on the duration of interest. The period is 6 hours for durations less than 6 hours and 12 hours for durations greater than 12 hours. For durations between 6 and 12 hours, use the duration as the period. The threshold rainfall is based on 1 mm per 6 hours.
3. Move outward from where the second period stopped to meet the third criteria; which is, the first 1 hour period with rain below the specified threshold of 0.01 mm/h.

This method was developed so that it could be automated for use in a computer search. Other methods have been used in earlier studies (see Appendix B) but these commonly had a subjective component.

The method of defining storms in the pre-burst project, differs from the way that storm events were defined in the ARR losses project (Project 6). Different approaches to event definition can have a strong influence on pre-burst estimates (Loveridge et al., 2015).

2.3. Critical bursts

The calculation of pre-burst rainfall depends on the identification of a "critical burst" for each candidate storm event. The critical burst is the rarest burst period (of any duration) within a complete storm.

An example explains how the critical burst is determined. Consider the 10 hour rainfall event of 46 mm shown in Figure 2. This is based on a pluviograph near Northcote, Victoria (Lat = -37.770, Long = 144.990). Each bar represents the amount of rain in 6 minutes.

We search through the storm to find the maximum amount of rain that falls in durations of 6 min, 12 min (2 consecutive 6 min periods), 18 min (3 consecutive 6 min periods) etc. This is shown in Figure 3.

Next, the annual exceedance probabilities are calculated that correspond to each of these rainfall depths for their durations. In this example, AEPs are based on the 2016 IFD data provided by the Bureau of Meteorology. The relationship between duration and AEP is shown in Figure 4.

Looking at Figure 4 there is a clear AEP peak. The rarest AEP of 19% occurs at a duration of 192 min and a rainfall depth of 34 min. The maximum 192 min period starts at the 3rd 6 min interval and ends at the 35th. The rainfall before this period, the pre-burst, is 0.2 mm and the post-burst is 11.35 mm. The pre-burst to burst ratio is 0.2 mm to 34 mm, 0.59%.

Note that this example, burst frequency was calculated using the latest, 2016, IFD data. For the ARR pre-burst project, the 2013 IFD data was used. The need to update the procedure to use the 2016 IFD values is recognised in ARR but that is yet to occur (See Book 2, Section 5.4).

The critical burst method of estimating pre-burst is not consistent with other approaches and there is some doubt that it produces unbiased results (see Section 2.8 and Appendix B). Each event has a single critical burst, so only contributes a single value of pre-burst rainfall. This is different to IFD analysis where a single event may to contribute information to determine the frequency of bursts for a range of durations.

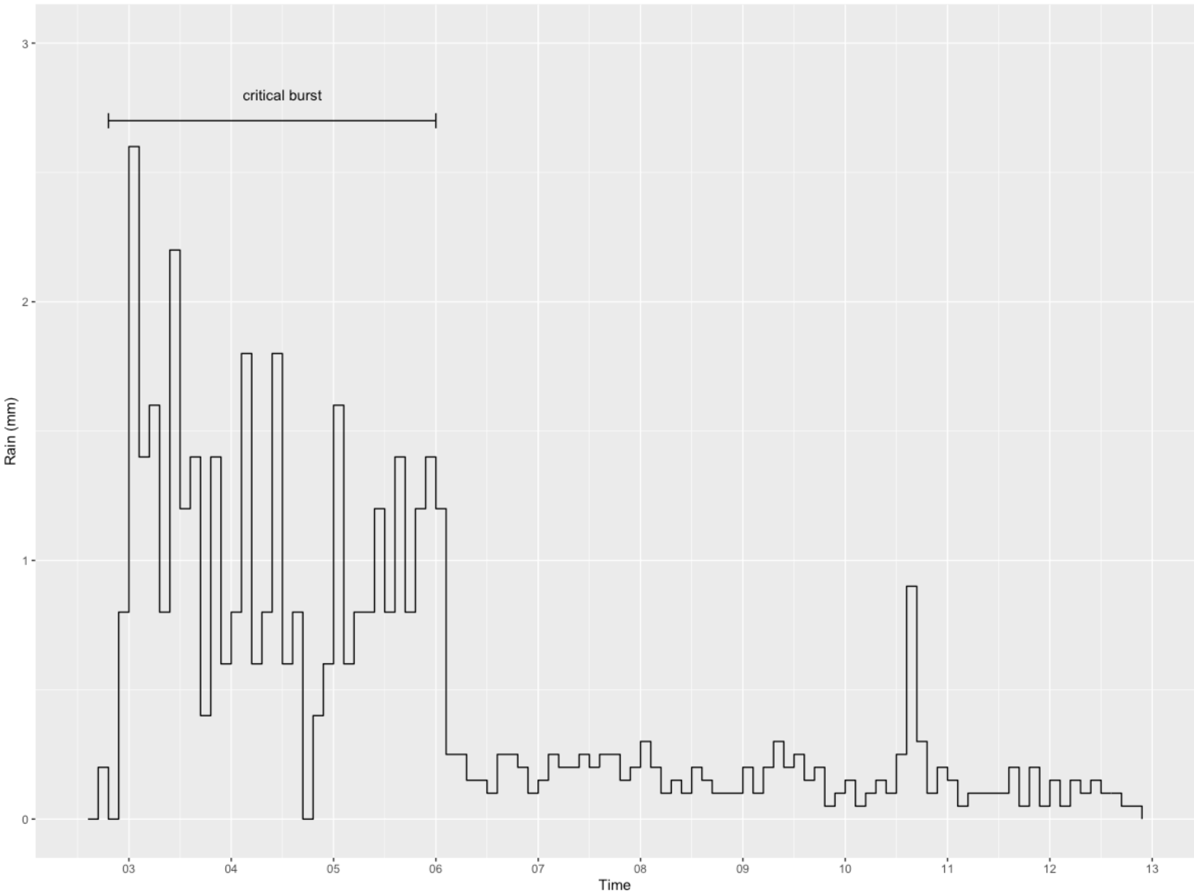

Figure 2: Storm with rain between 2:20 am and 1 pm. Graph shows rainfall depth (mm) every 6 min

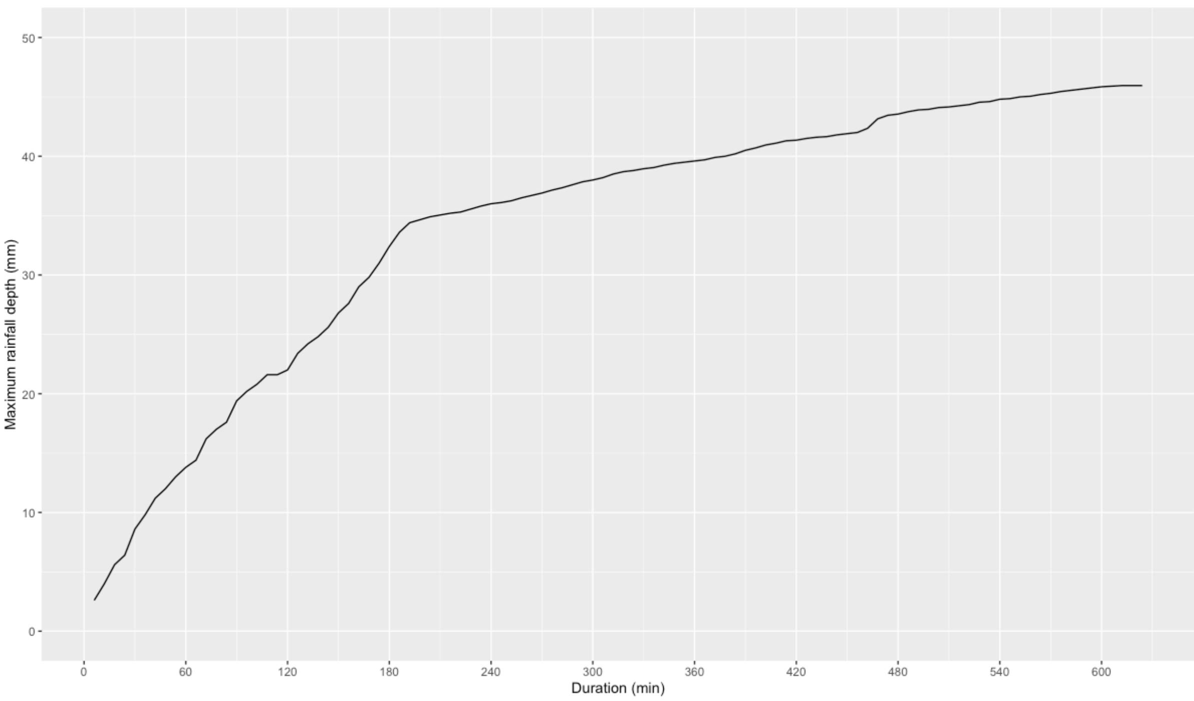

Figure 3: Maximum rainfall for each duration

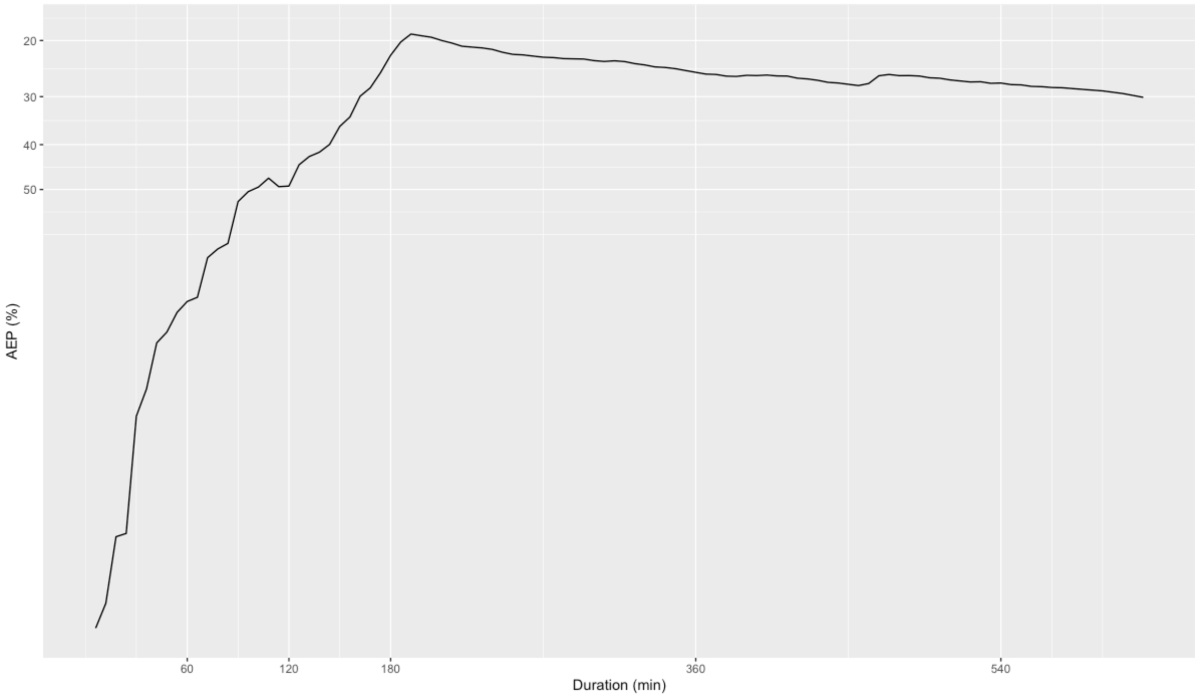

Figure 4: Annual exceedance probability of the rainfall depth at each duration

2.4. Pre-burst binning

Pre-burst values are collected into duration-AEP bins. Pre-bursts are collated for 11 durations and 6 AEPs, thus 66 bins in total.

Durations (minutes):

> 60, 90, 120, 180, 360, 720, 1080, 1440 (24 hours), 2160 (36 hours), 2880 (48 hours), 4320 (72 hours).

AEPs (%)

> 50, 20, 10, 5, 2, 1.

Note that the duration bins are not the same as those used to classify storms in the national storm database (Table 1). Also note that the bin range is limited; for example, there is no information for durations less than 60 min or durations rarer than 1% AEP. This limited range of durations and AEPs can make application of pre-burst values challenging as discussed below.

In the example in Section 2.3, a critical burst of 192 min (3.2 hours), with an AEP of 19% means the pre-burst rainfall for this event would be considered for inclusion in the 180 min, 20% AEP bin (see Table 1).

2.5. Pre-burst values across Australia

ARR project 3 provided pre-burst rainfall values for a grid defined over the whole of Australia. In areas where there is dense coverage by pluviographs, the grid spacing is 0.2 degrees, increasing to 0.5 degrees in sparse areas (Figure 5).

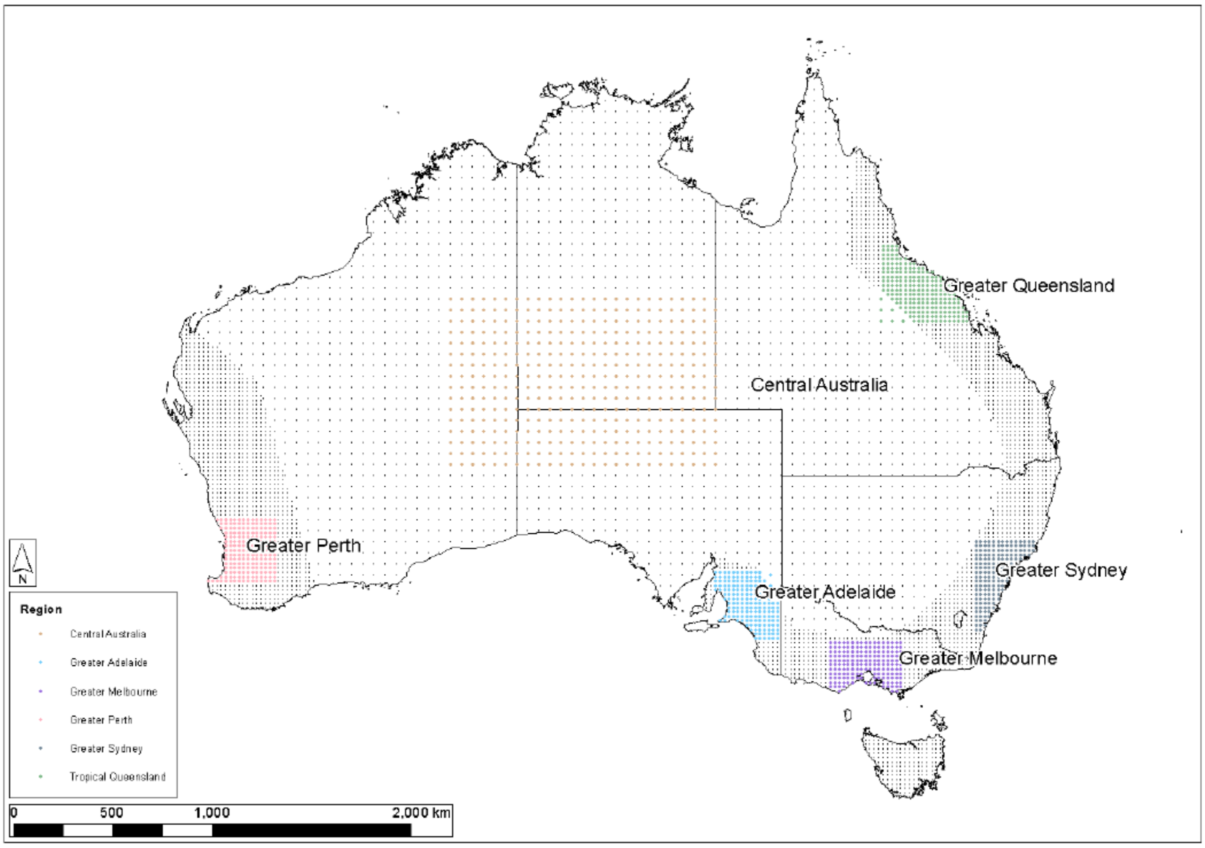

Figure 5: Grid points were pre-burst values are provided (source: Figure 2-3, Loveridge et al., 2015c)

For each grid point, 40 storms were selected from the national storm database for each of the 66 duration-AEP bins. Candidate storms were ranked using three equally weighted similarity measures:

1. Distance: events were favoured that occurred closer to the grid point of interest. Only storms within 500 km of the grid point were considered.
2. AEP similarity: the similarity of the AEP of the critical burst to the AEP of the bin. The AEP that was calculated used the IFD relationship at grid point combined with the depth of the critical burst at the location where it occurred.
3. IFD similarity: The similarity between the IFD relationship at the location of the storm and at the location of the grid cell.

Once the most similar 40 storms were identified at a grid point, the 40 pre-burst values were extracted and used to calculate the median pre-burst depths and ratios.

As well as the median values, the distribution of pre-burst depths and ratios were also determined from the 40 values; that is, some key percentiles, 10^{th}, 25^{th},75^{th} and 90^{th} were estimated. Using only 40 values to identify extreme percentiles such as the ninetieth and tenth percentiles will mean these estimates are uncertain. Other approaches, involving regionalising or pooling data were investigated but where found not be appropriate (Loveridge et al., 2015a;2015c).

2.6. Example pre-burst values

As an example, pre-burst depths and ratios, were obtained from the ARR data hub[5] and are presented for the grid point at the centroid of the Axe Creek Catchment near Bendigo Lat -36.833,

5 https://data.arr-software.org

Lon 144.377 (see Table 2 and Figure 6 for depths and Table 3 and Figure 7 for ratios). The values in each cell of the tables are based on the top 40 storms appropriate for the duration and AEP of that cell.

The graphs show substantial variation with duration and AEP. The median initial loss for this catchment is 27[6] mm so, in this case, the median pre-depths are much smaller than the initial loss.

A summary of results across all the Project 6 sites are shown in Figure 8 and Figure 9. There is a pattern across all sites, particularly noticeable for ratios, where for short durations, frequent events have larger pre-burst than less frequent events. For longer durations, it is the opposite. The switch occurs around 360 min. The reason for this is unknown.

Table 2: Median pre-burst depths for Axe Creek at Sedgewick. All depths are in mm

Duration (min)	Duration (hours)	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP
60	1	4.4	3.6	3.1	2.6	1.9	1.3
90	1.5	2.3	1.8	1.5	1.2	0.9	0.7
120	2	3.2	3.6	3.9	4.2	2.4	1.1
180	3	1.5	3.0	4.0	5.0	5.2	5.4
360	6	0.8	1.7	2.3	2.9	3.8	4.5
720	12	0.0	0.9	1.5	2.1	3.2	4.0
1080	18	0	0.3	0.5	0.7	0.9	1.1
1440	24	0	0	0.1	0	0.1	0.2
2160	36	0	0	0	0	0	0
2880	48	0	0	0	0	0	0
4320	72	0	0	0	0	0	0

6 As obtained from the data hub 20 Apr 2020.

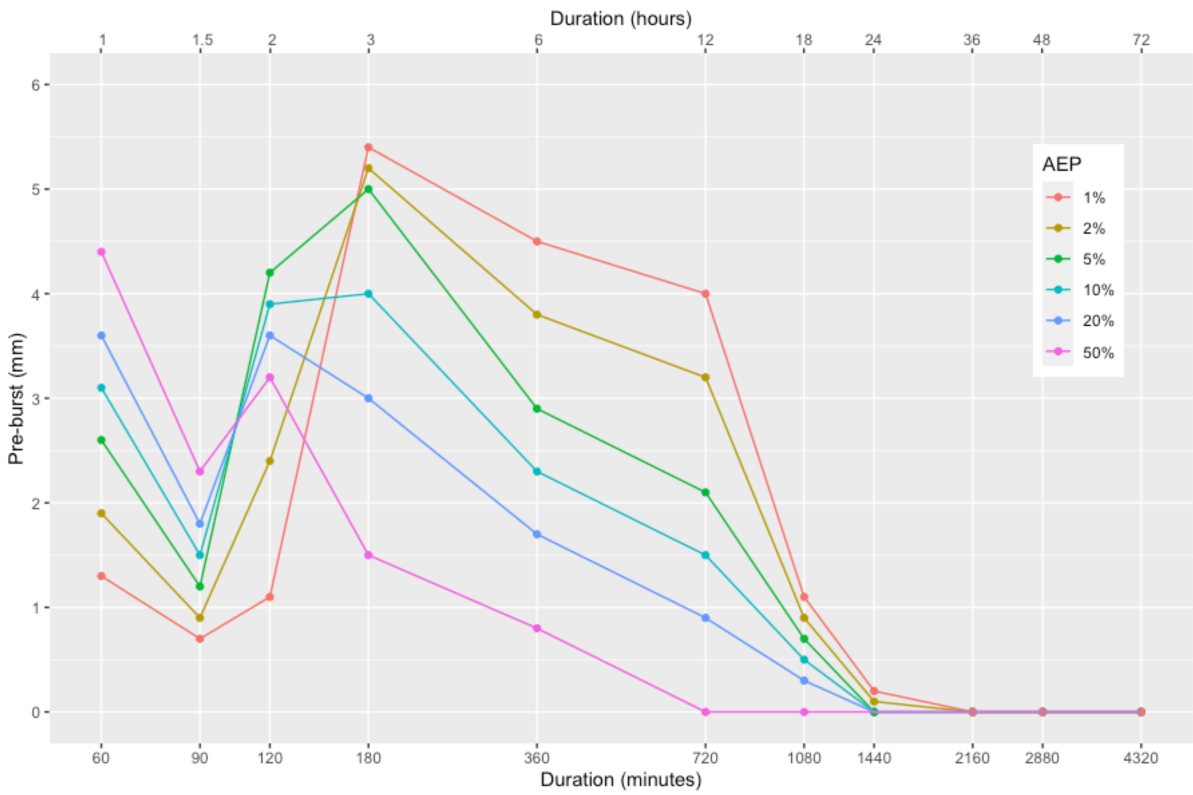

Figure 6: Median pre-burst depths for Axe Creek at Sedgewick

Table 3: Median pre-burst ratios for Axe Creek at Sedgewick.

Duration (min)	Duration (hours)	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP
60	1	0.276	0.153	0.105	0.073	0.041	0.024
90	1.5	0.124	0.066	0.044	0.029	0.017	0.011
120	2	0.161	0.125	0.109	0.097	0.044	0.017
180	3	0.067	0.092	0.100	0.103	0.087	0.078
360	6	0.028	0.042	0.047	0.050	0.054	0.056
720	12	0	0.018	0.025	0.029	0.038	0.043
1080	18	0	0.005	0.007	0.009	0.010	0.011
1440	24	0	0.000	0.001	0.000	0.001	0.002
2160	36	0	0	0	0	0	0
2880	48	0	0	0	0	0	0
4320	72	0	0	0	0	0	0

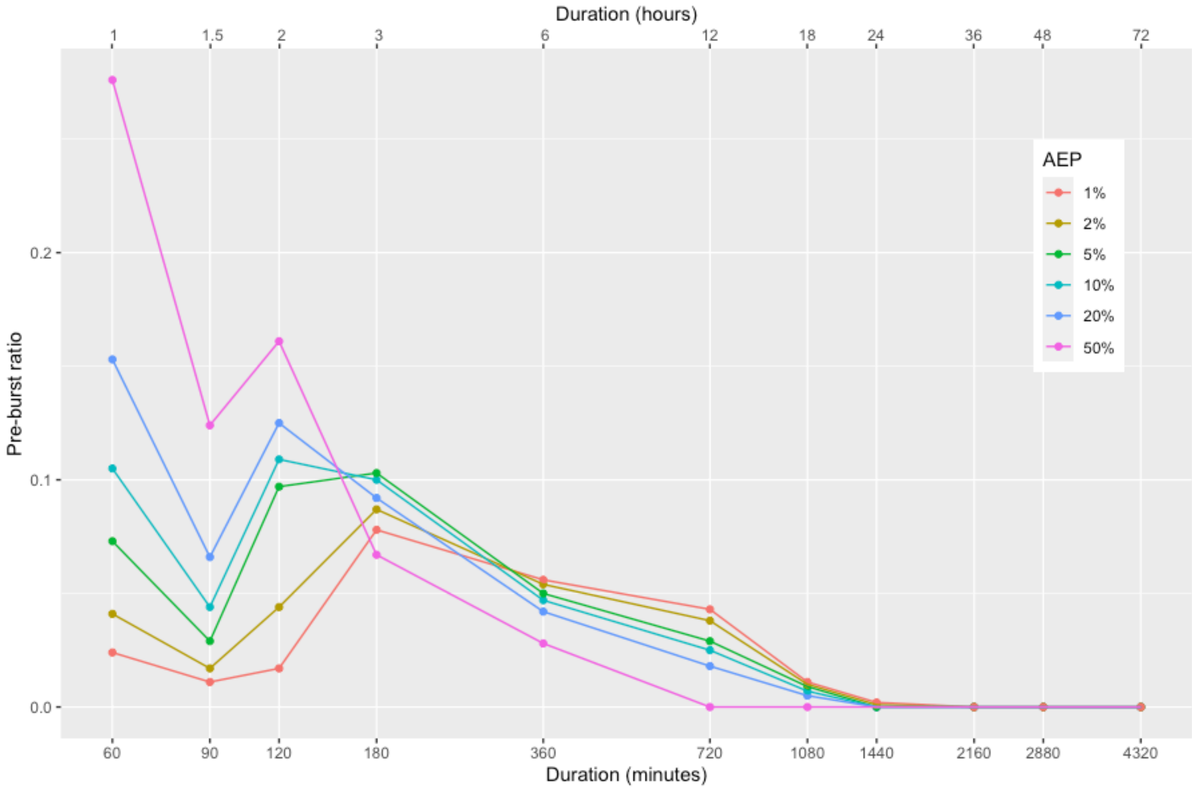

Figure 7: Median pre-burst ratios for Axe Creek at Sedgewick

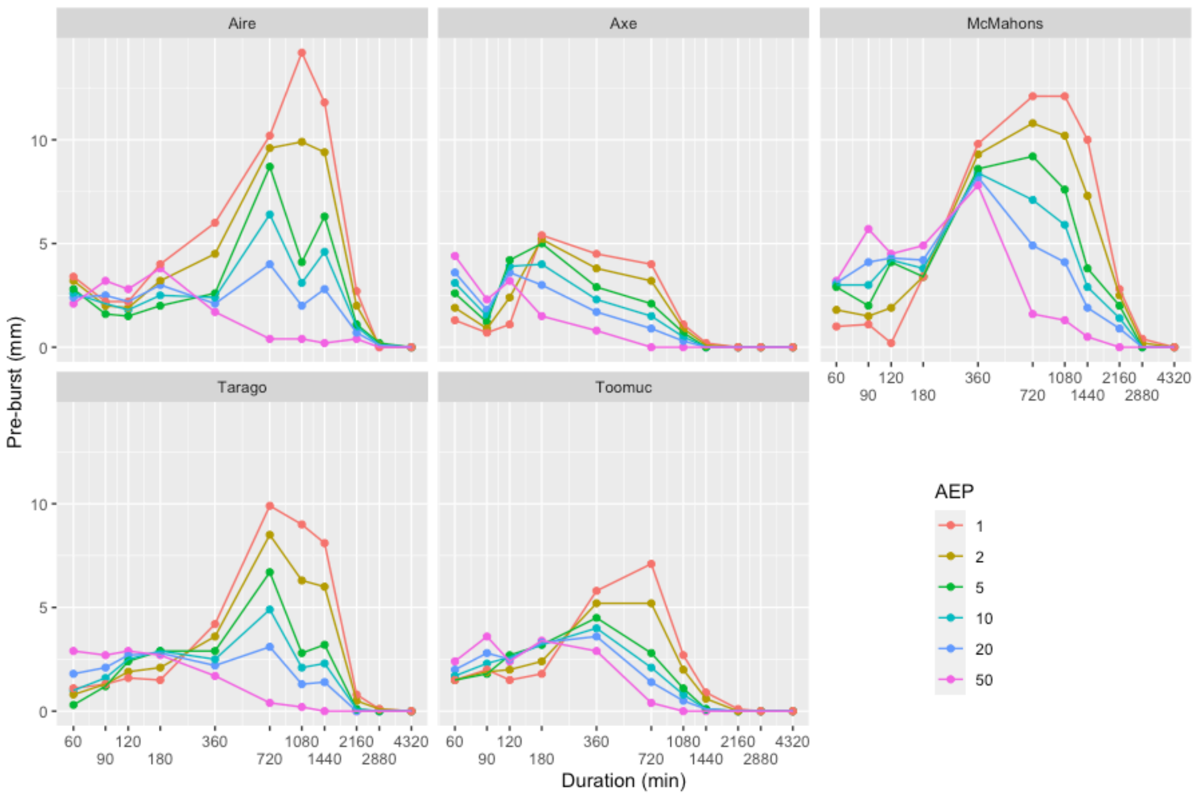

Figure 8: Median Pre-burst depths for all Project 6 catchments

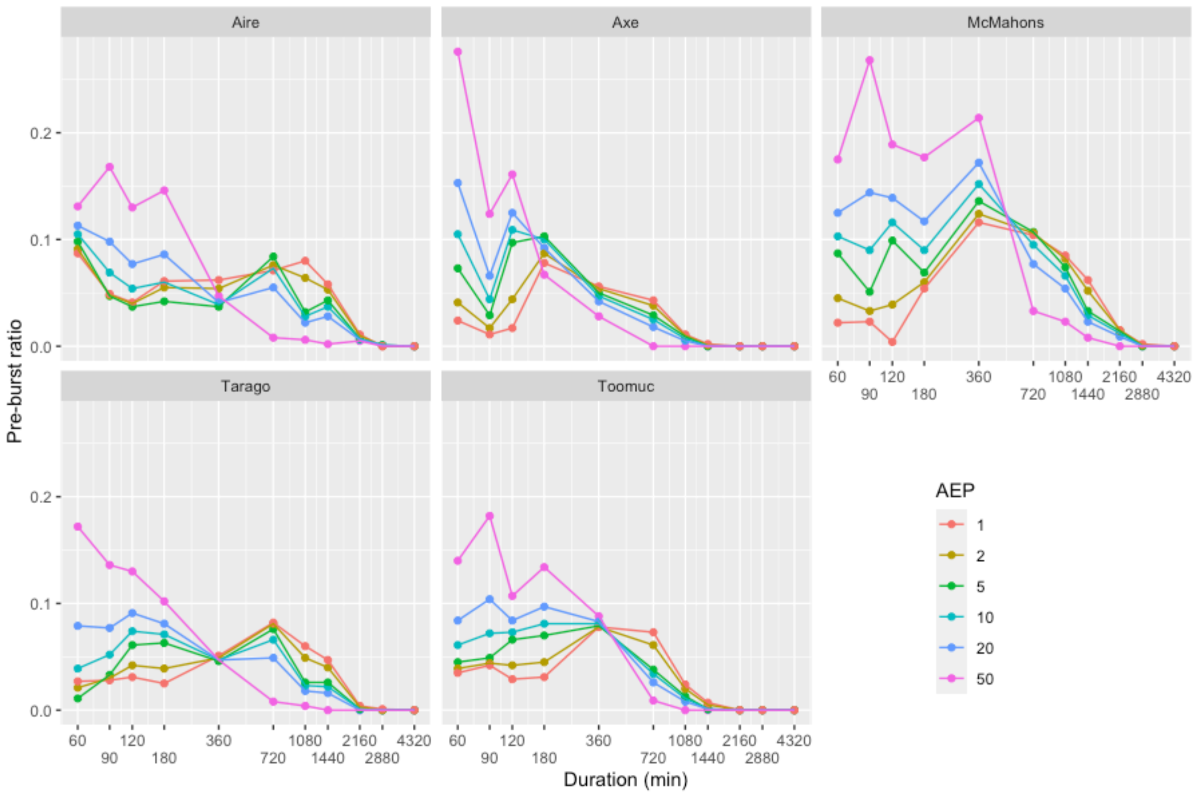

Figure 9: Median Pre-burst ratios for all Project 6 catchments

Pre-burst distribution

Information on the distribution of depth and ratio is also available. Taking the 60 min, 50% AEP values as an example, the distribution of pre-burst depth is shown in Table 4. The 0th and 100th percentile values are not available from the data hub but are required for randomly generating pre-burst depth as part of a Monte Carlo modelling process. These values have been linearly extrapolated as shown on Figure 10.

The distribution of pre-burst depths are shown as a cumulative distribution function (Figure 10) and as a histogram, based on 10,000 randomly generated pre-burst values (Figure 11). The median of the values in the histogram is 4.4 mm, which as expected, is median pre-burst for this combination of duration and AEP.

This histogram shows that most pre-burst values are small but occasionally can be a substantial proportion of the initial loss. For example 15% of values are 20 mm or more, compared to a storm initial loss of 27 mm. These large pre-burst values are likely to have a significant influence on modelled runoff.

Table 4: Distribution of pre-burst depth and ratio for duration = 60 min, AEP = 50%

Percentile	Depth	Ratio
0	0 (extrapolated)	
10	0	0
25	0	0
50	4.4	0.276
75	13.9	0.864
90	23.5	1.486
100	29.9 (extrapolated)	

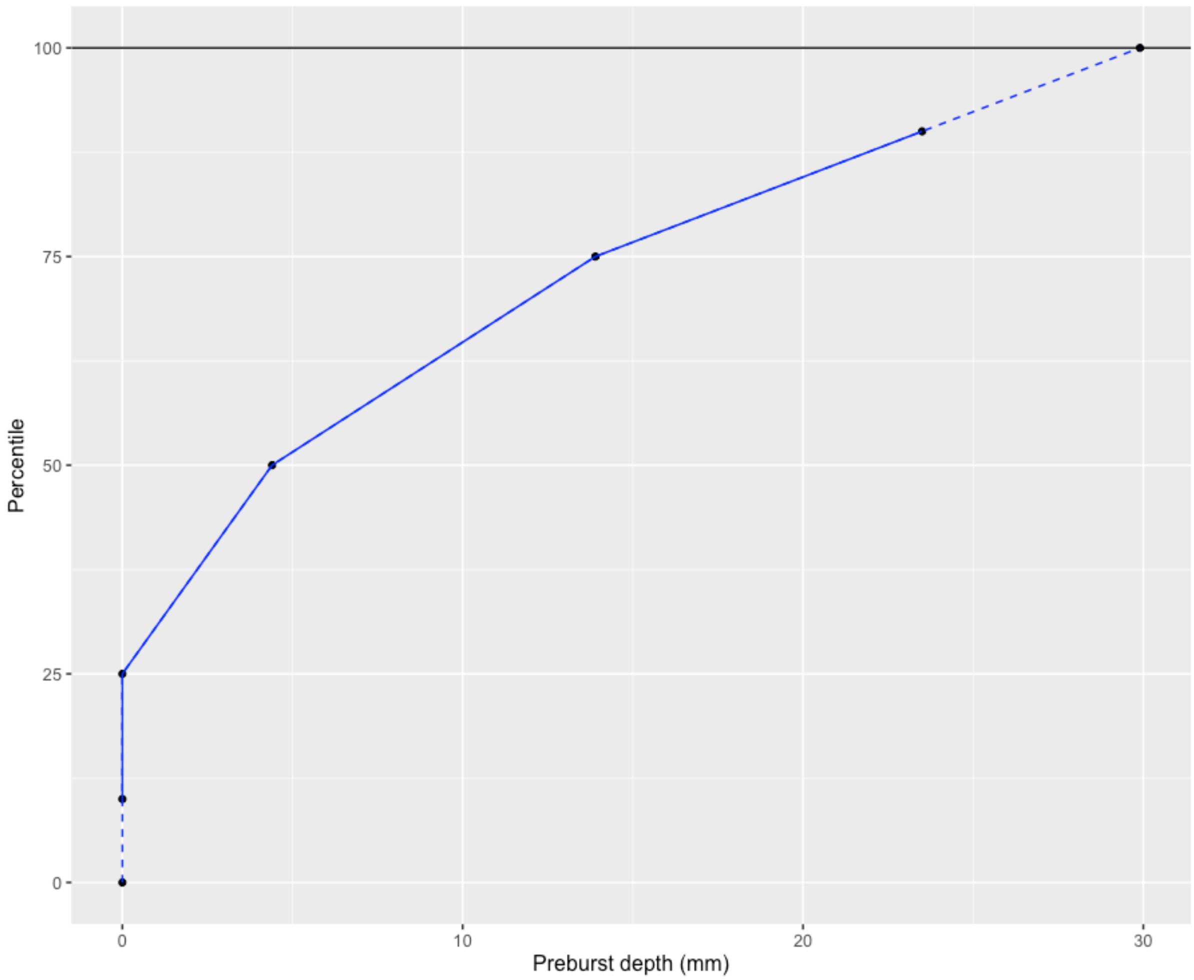

Figure 10: Distribution of pre-burst depth for Axe Creek as a cumulative distribution function

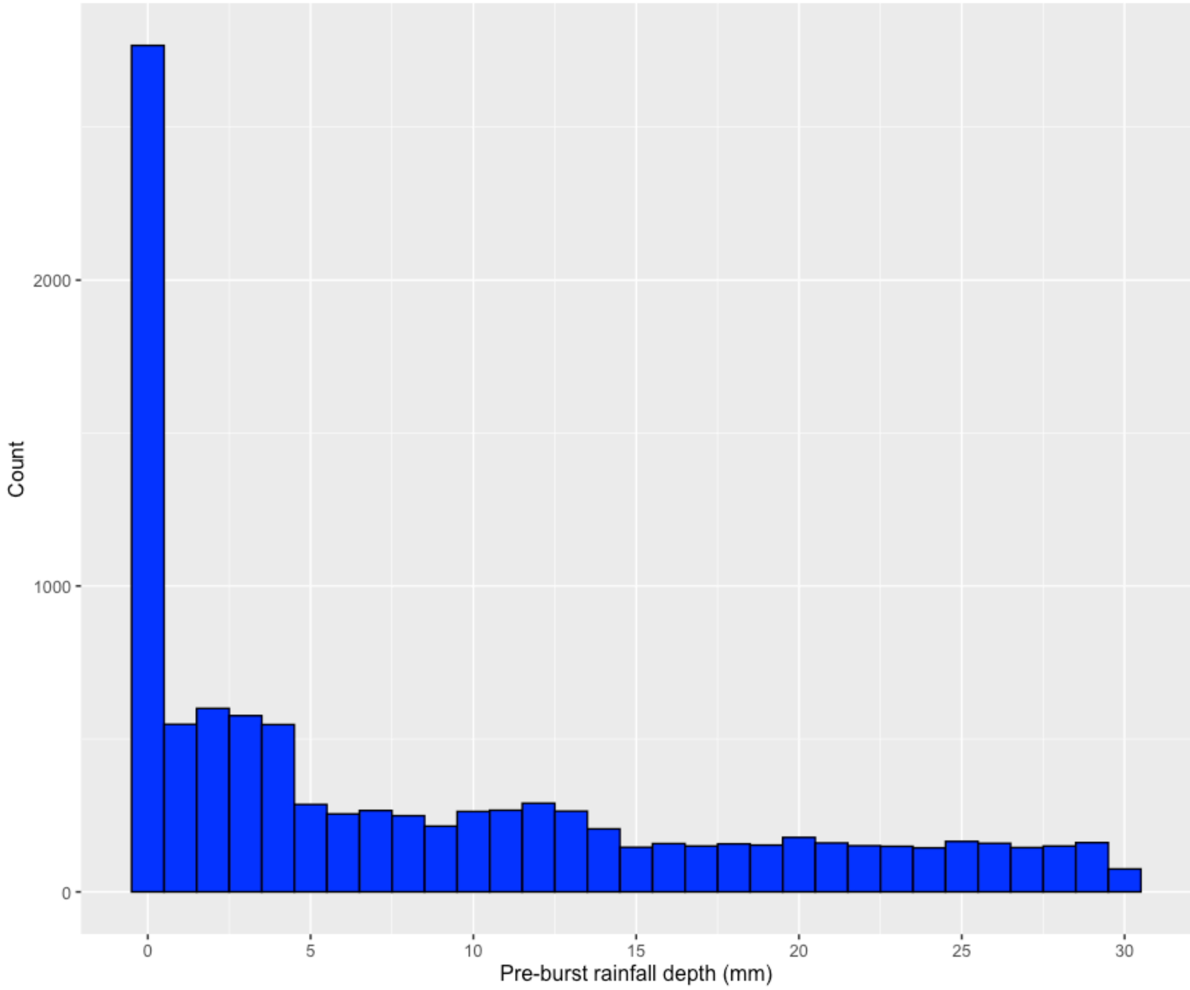

Figure 11: Distribution of pre-burst value based on a histogram of 10,000 randomly generated pre-burst values

As well as considering the pre-burst values at a single point, the spatial distribution of pre-burst is interest. Pre-burst values were obtained from the ARR data hub for a transect across Victoria (Figure 12). The median and percentile pre-burst depths are shown in Figure 13. The median pre-burst values are small in the dryer parts of the state, rising to over 20 mm in Alpine areas and in the east. For example, a location near Mallacoota (-37.521N, 149.656E), the median storm initial loss is 17 mm, the median pre-burst for a 12 hour duration 1% AEP burst is 24.5 mm and the 90th percentile pre-burst is 120.4 mm. Clearly, these pre-burst values, which are larger than the median storm initial loss, are likely to have a significant influence on runoff. Further transect information is provided in Appendix C.

Figure 12: Transect across Victoria used to explore pre-burst values

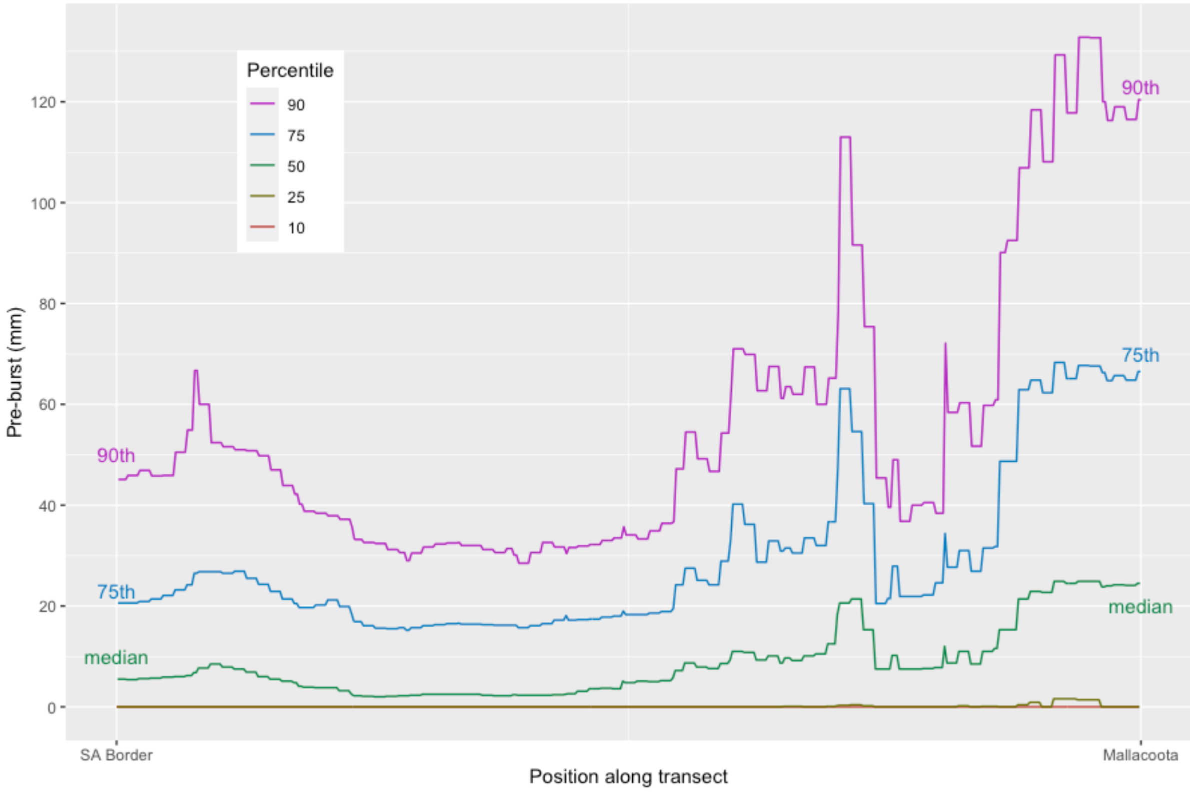

Figure 13: Pre-burst values along the transect for the 12 hour, 1% AEP burst

2.7. Relationship between pre-burst ratio and burst AEP

The relationship between pre-burst ratio (the ratio of pre-burst depth to burst depth) and burst AEP is an important consideration in flood modelling. Some previous studies have suggested that the pre-burst ratio is independent of burst AEP (Srikanthan and Kennedy, 1991; Minty and Meighan, 1999; Scorah et al., 2015). This makes it straightforward to scale pre-burst values with burst severity.

For the ARR pre-burst data, the available evidence does not support the hypothesis of a constant pre-burst ratio. Pre-burst ratios were obtained from the data hub for 26 catchments used in the ARR benchmarking study (Figure 14). This suggests that for durations 12 hours and longer, pre-burst ratios increase as AEP becomes rarer. For durations 3 hours and shorter, ratios decrease as bursts become rarer. The 6 hour ratios seem reasonably constant with AEP. The ratios are also constant, and near zero for durations long than 24 hours.

When using pre-burst values for modelling, the scaling of pre-burst values with storm severity is important, particularly for events outside of the range of AEP values provided on the data hub.

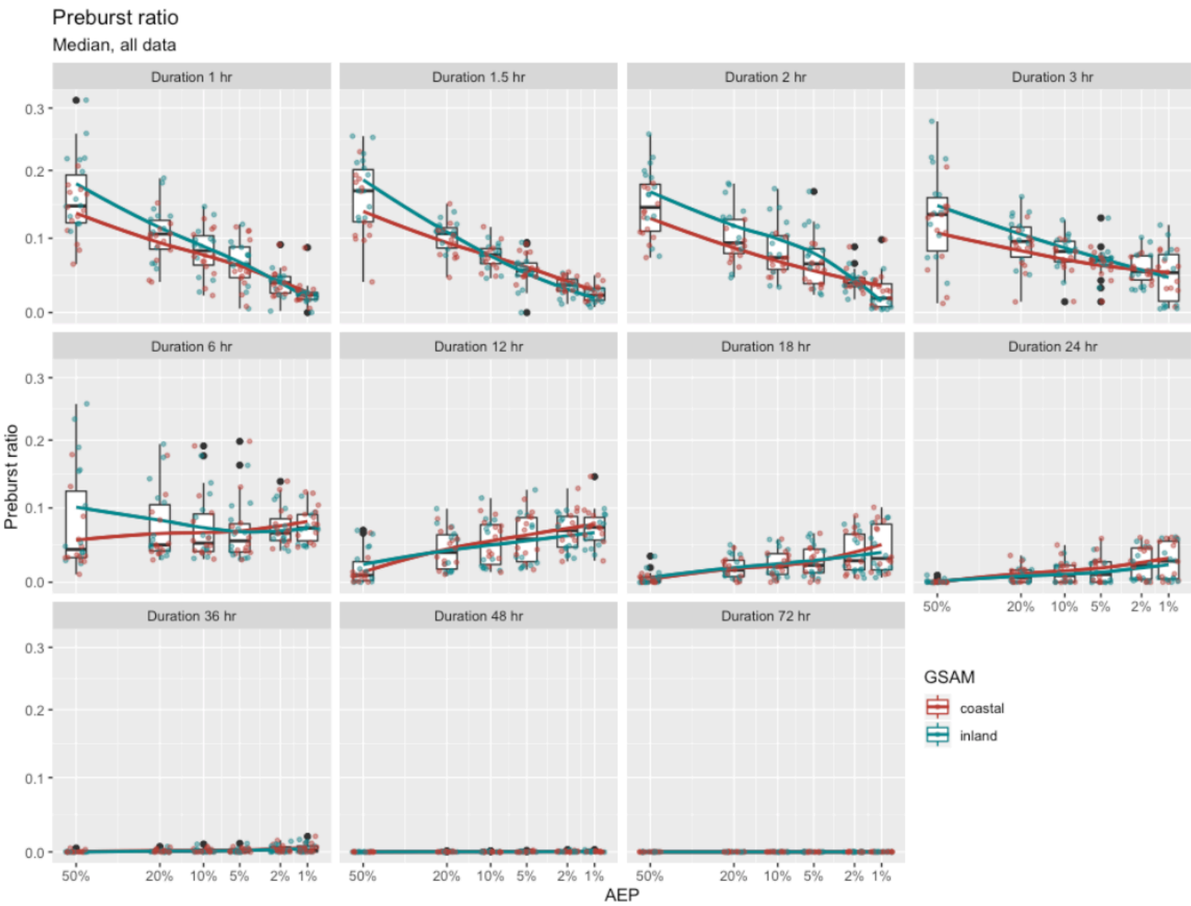

Figure 14: Pre-burst ratios as a function of AEP for a range of durations for 26 catchments considered as part of the ARR benchmarking project. Also noted is whether catchments are in the GSAM coastal or inland region

2.8. Limitations of ARR pre-burst values

There are several limitations and uncertainties associated with the pre-burst values provided by ARR 2019. These make it challenging for practitioners to have confidence in the data and suggest that more work is required to finalise the values and ensure they are suitable for modelling.

- Lack of verification

  The report on pre-burst analysis was never finalised, verified or publicly released. A draft is available but that was obtained through personal contacts (Loveridge et al., 2015c).

- Reliance on outdated IFD data

  Estimates of burst severity are based on the now superseded 2013 IFD values. The need to update the analysis to use 2016 IFD data is acknowledged in ARR (Book 2, Chapter 5.4).

- The use of *critical bursts* to determine pre-burst rainfall depth

  ARR acknowledges that the use of the critical burst approach is problematic (Book 2, Chapter 5.4):

  > *The pre-burst was characterised based on the rarest rainfall duration burst within the storm using the 2013 IFDs. Hill et al. (2015) found this approach gave a biased estimate of the average pre-burst, systematically underestimating the depth of the pre-burst. Following from this work and the expected update of the IFDs from the Bureau of Meteorology in 2016 this work will be updated…*

  The pre-bursts analysis is yet to be updated, so practitioners are left using information that is known to be biased. Unfortunately the reference to Hill et al. (2015) seems to be incorrect as that paper does not mention the problem associated with the use of critical bursts. It is not clear where this analysis was reported.

- Sensitivity of pre-burst data to storm and event definitions

  Loveridge et al. (2015a) report on an investigation into the sensitivity of storm definitions and found they had a dramatic effect on design flood estimates. Storm definitions determine the start and end points of events which has implications for the amount of pre-burst.

  Burst definitions are also important. ARR used a critical burst approach based on the most intense period considering any duration. An alternative is to define bursts as the rarest period of rainfall for each duration. It is also important to consider if embedded bursts should be allowed, i.e. shorter periods within a burst with rainfall that is much rarer than the burst as a whole.

- Different definitions used in the pre-burst and losses projects

  The ARR pre-burst and temporal pattern projects use the same storm and event definitions, but these differ from those used to derive losses (Loveridge et al. 2015a; 2015c; Hill et al., 2014; Scorah et al., 2015).

  There is a comment in Loveridge et al. (2015c) that: "the current [pre-burst] study is not suitable for use with ARR recommended design losses". It is not clear if this comment applies to the pre-burst estimates on the data hub but it is concerning that it may and it is concerning that it is in print without a clear statement in ARR that the pre-burst values are, in fact, appropriate.

- Limited range of durations

  Pre-burst data is only available for durations from 60 to 4320 min (1 to 72 hours). This is a particular problem for modelling of small urban catchments where storm durations less than 60 min are often important. Practitioners are forced to extrapolate to smaller durations with little guidance, resulting in inconsistent approaches between studies

- Limited range of AEPs

  Pre-burst data is available for AEPs from 50% to 1%. This is insufficient for many modelling applications. When using Monte Carlo modelling approaches, it is usually necessary to estimate rainfalls, and hence pre-bursts out to 1 in 2000 AEP to obtain reliable estimates of the 1% flood. By necessity, practitioners are developing their own procedures to do this creating inconsistencies.

  The interim approach used in this study, to estimating pre-burst values for AEPs rarer than 1%, was to hold the pre-burst to burst ratio constant at the 1% AEP value.

3. Comparison of Project 6 and Project 3 pre-burst values

As noted earlier, the information on pre-burst and losses provided in ARR was derived in separate projects and there is concern about the different approaches to storm definitions that have been used. The key point is, if the data hub losses are to be used in modelling, rainfall inputs to models must be defined in a way that is consistent with the definition of rainfall events in the losses project. The intimate connection between the definitions of storms and losses is shown in Figure 1. If we change the storm definition e.g. starting a storm earlier, then the amount of loss is likely to change.

This section compares the pre-burst values from the losses project (Project 6) with those values from Project 3. Project 3 is the source of the pre-burst data on the data hub, while Project 6 is the source of the data hub loss values (Hill et al., 2016). There are five locations in Victoria where this comparison can be made. (Figure 15, Table 5).

Figure 15: Victorian sites used in the losses project (Project 6)

Table 5: Victorian catchments used in the losses project (Project 6)

Catchment	Gauge	GSAM Region	Catchment Area (km^2)	Gauge		Catchment centroid	
				Latitude	Longitude	Latitude	Longitude
Aire	235219	Coastal	90	-38.703	143.477	-38.662	143.545
Axe	406216	Inland	34	-36.898	144.357	-36.833	144.377
McMahons	229106	Coastal	40	-37.738	145.885	-37.748	145.895
Toomuc	228217	Coastal	42	-38.065	145.462	-38.094	145.469
Tarago	228206	Coastal	78	-37.967	145.933	-37.956	145.887

3.1. The Australian Rainfall and Runoff losses project

Project 6 investigated initial and continuing losses on 38 catchments around Australia including 5 catchments in Victoria (Hill et al., 2014; 2015; 2016). The procedure was to obtain historical rainfall events, and the measured runoff that occurred in response to these events. Loss estimates were treated as parameters in hydrologic modelling with adopted loss values being those that resulted in the best fit between measured and modelled discharge. Median loss values from the 38 catchments were then used to provide estimates of losses for the non-arid areas of Australia. These loss estimates are available on the ARR data hub.

The losses project always envisaged that losses would be part of a complete storm approach to modelling. That is, practitioners would obtain burst rainfalls based on IFD relationships, and then prepend the appropriate pre-burst values to create complete storms. These complete storms would be used as model inputs along with the design values of initial and continuing losses obtained from the data hub. Unfortunately, other aspects of ARR moved away from complete storm modelling to a burst modelling approach. This has resulted in potentially confusing advice being provided in ARR and inconsistencies in storm definitions used in temporal patterns and pre-burst, compared with losses.

3.2. Comparing pre-burst values

It is possible to compare the data hub and Project 6 pre-burst values. This uses the method described in Scorah et al. (2015).

The definition of events used in Project 6 differs from that used for Project 3 as described in Section 2.2. In summary, for Project 6:

- Pluviograph records were obtained for each of the 38 project sites
- The largest n bursts were identified for each duration, where n is the number of years of pluviograph record
- Start time was selected subjectively based on approximately 12 hours of no significant rainfall
- End time was selected subjectively based on when streamflow had effectively ended
- Start times where moved to 9am to allow incorporation of daily rainfall data.

A range of burst durations was considered: 3, 6, 12, 24, 48, 72 hours.

Scorah et al. (2015) found a consistent decreasing trend of pre-burst ratio with duration, and an invariance with AEP. This contrasts with the data hub pre-burst ratios which show substantial variation with duration and AEP (see Figure 9).

At each of 38 sites, 20 to 30 complete storms were identified for each duration, with some overlap between durations. From these storms, it is possible to identify pre-burst, burst and post-burst rainfall. For the same locations it is also possible to obtain the pre-burst estimates for the Project 6 sites from the data hub.

Pre-burst values are compared in Table 6 for the Victorian sites, which provides the median values from each source, along with an estimate of the range and a bootstrap estimate of the confidence interval for the Project 6 median.

Although the median values differ, in most cases, the data hub pre-burst value is within the 95% confidence interval of the Project 6 median value. Highlighted values in the table show where this is not the case. For the Aire River, the Project 6 pre-burst values are consistently higher than those from the data hub, particularly for bursts of 3 hours duration.

Pre-burst values are compared graphically in Figures 19 to 23. The pre-burst values appear to be similar between the two sources apart from the short duration events for the Aire River.

A possible cause of the differences for the Aire River relates to its coastal location. Data hub pre-burst values are calculated using storm data transposed from nearby sites. For a site on the coast, donor sites will likely be from further inland where pre-burst is smaller. There is evidence for this from the location of pluviographs within 500 km of Aire River that were used to determine three-hour temporal patterns in the south coast region (Figure 16). It is likely that a similar set of sites was used to determine pre-burst.

Figure 16: Locations of pluviographs used to determine 30 min temporal patterns within 500 km of the Aire River catchment

Although there are issues for the Aire River site, the reasonably consistent results for the other sites suggests that as an interim, it may be appropriate to use the ARR pre-burst values, along with ARR losses, with the caveat that there will be issues in some area of Victoria.

A further issue is the extrapolation of data hub pre-burst. The results from Scorah et al. (2015) show invariance with AEP and a consistent scaling with duration. This justifies straightforward extrapolation. In contrast, the inconsistent relationship between data hub pre-burst, duration and AEP makes extrapolation hard to justify.

Findings from the ARR benchmarking project will clarify this further.

Table 6: Comparison of pre-burst values from Project 6 with those from the data hub (highlighted rows show where there is a significant difference between data hub and Project 6 data

	Project 6 Data			Data hub	
Burst duration (hour)	Pre-burst range (mm)	Median Pre-burst (mm)	95% confidence interval for Median Pre-burst (mm)	Median Pre-burst[7] (mm)	Pre-burst range[8] (mm)
Aire River n = 36					
3	0 – 162.6	31.7	14.6 - 42.4	3.1	0 – 40.2
6	0 – 105.9	17.4	10.4 - 35.5	2.5	0 – 49.5
12	0 – 128.9	15.5	9.2 - 27.0	7.55	0 – 74.6
24	0 – 99.5	6.3	1.8 - 10.9	5.45	0 – 58.7
48	0 – 79.4	1.7	0.3 - 2.6	0.1	0 – 40.6
72	0 – 73.6	0.3	0 - 2.2	0	0 – 43.9
Axe Creek n = 23					
3	0 – 146	8.2	1 - 17.8	4.5	0 – 51.3
6	0 – 46.6	2.6	0 - 7.4	2.6	0 – 49.5
12	0 – 96	1.8	0 - 5.3	1.8	0 – 34.4
24	0 – 96	0	0 - 3.4	0	0 – 26.2
48	0 - 71.6	0	0 - 0.2	0	0 – 7.3
72	0 – 29.6	0	0 - 0.04	0	0 – 15.8
McMahons n = 31					
3	0 – 68.4	1.8	0 - 5.4	3.6	0 – 44.3
6	0 – 74.4	9.0	0.4 - 16.2	8.5	0 – 59.6
12	0 – 64.4	9.2	1.2 - 11.4	8.15	0 – 77.6
24	0 – 62.8	6.5	0.4 - 9.6	3.35	0 – 61.8
48	0 – 38.4	0.0	0 - 0.7	0	0 – 21.9
72	0 – 23.6	0.0	0 - 0.4	0	0 – 23.5
Tarago n= 24					
3	0 – 68.4	5.7	2.1 - 13.2	2.75	0 – 35.6
6	0 – 74.4	9.4	1.4 - 17.6	2.7	0 – 42.7
12	0 – 64.4	8.1	1.2 - 13.3	5.8	0 – 61.9
24	0 – 62.8	0.8	0.4 - 3.9	2.75	0 – 41.6
48	0 – 38.4	0.0	0 - 0.1	0	0 – 39.7
72	0 – 23.6	0.0	0 - 0.4	0	0 – 25.9
Toomuc n = 33					
3	0 – 138.6	5.0	0.4 - 13.1	3.2	0 – 43.9
6	0 – 114.6	9.4	0.4 - 15.0	4.25	0 – 40.9
12	0 – 43.0	3.0	0.4 - 6.2	2.45	0 – 39.3
24	0 – 74.8	3.0	0.3 - 5.3	0.1	0 – 30.4
48	0 – 33.2	0.0	0 - 0.8	0	0 – 19.2
72	0 – 26.8	0.0	0 - 0.2	0	0 – 10.5

7 The data-hub medians are the median of each of the medians provided for the AEPs of 50%, 20%, 10%, 5%, 2% and 1%.

8 For data-hub pre-burst, the range is the determined from the pre-burst values across all percentiles and AEPs. This is likely an underestimate of the true range of the raw data

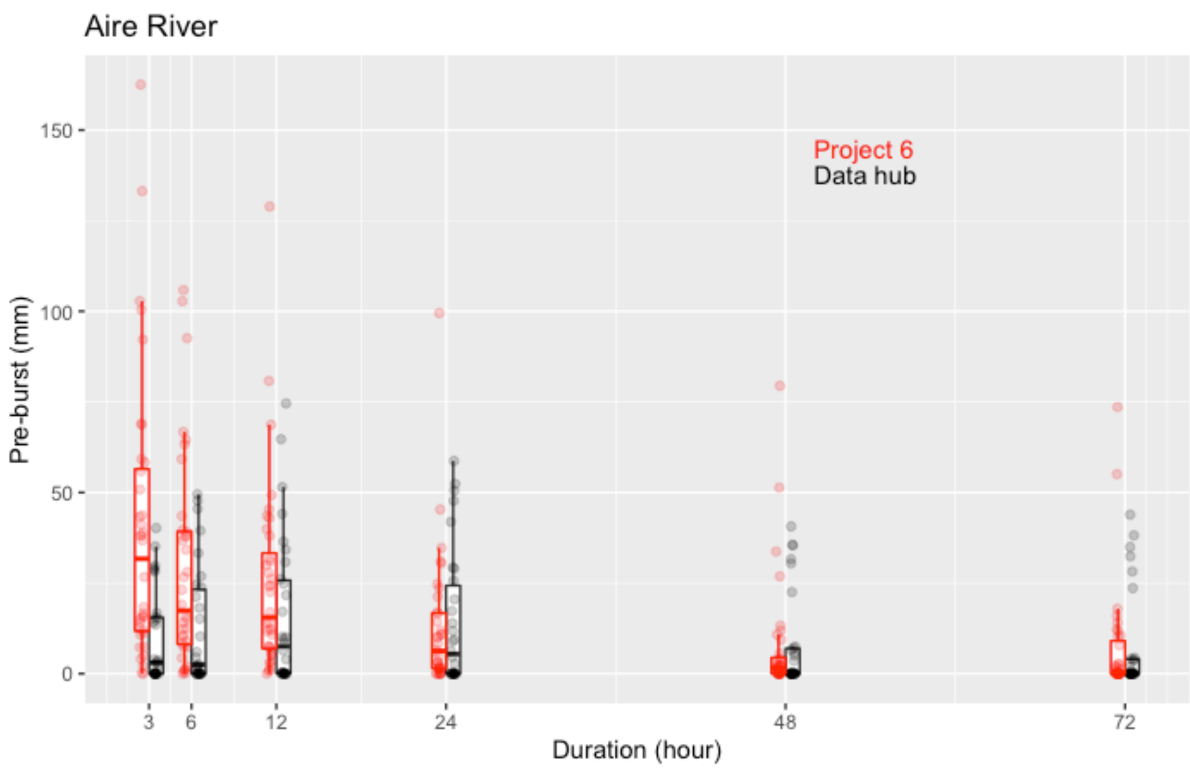

Figure 17: Aire River: comparison of pre-burst values from Project 6 and the data hub

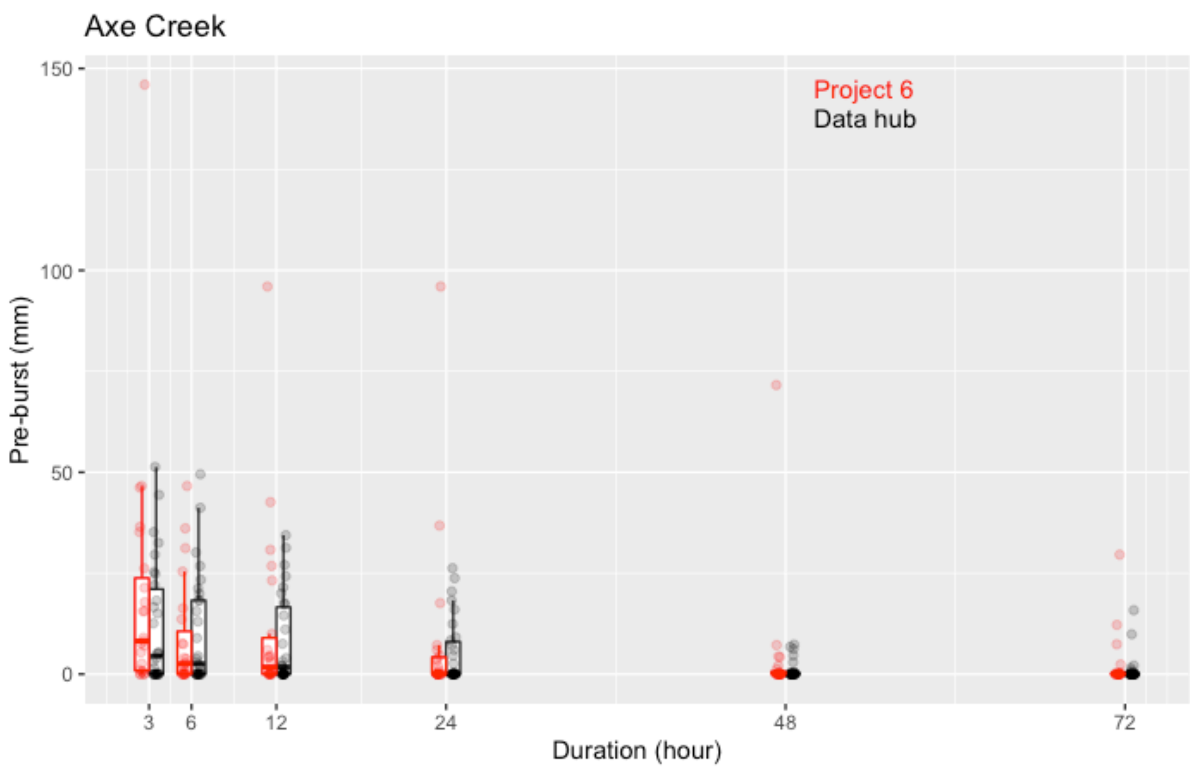

Figure 18: Axe Creek: comparison of pre-burst values from Project 6 and the data hub

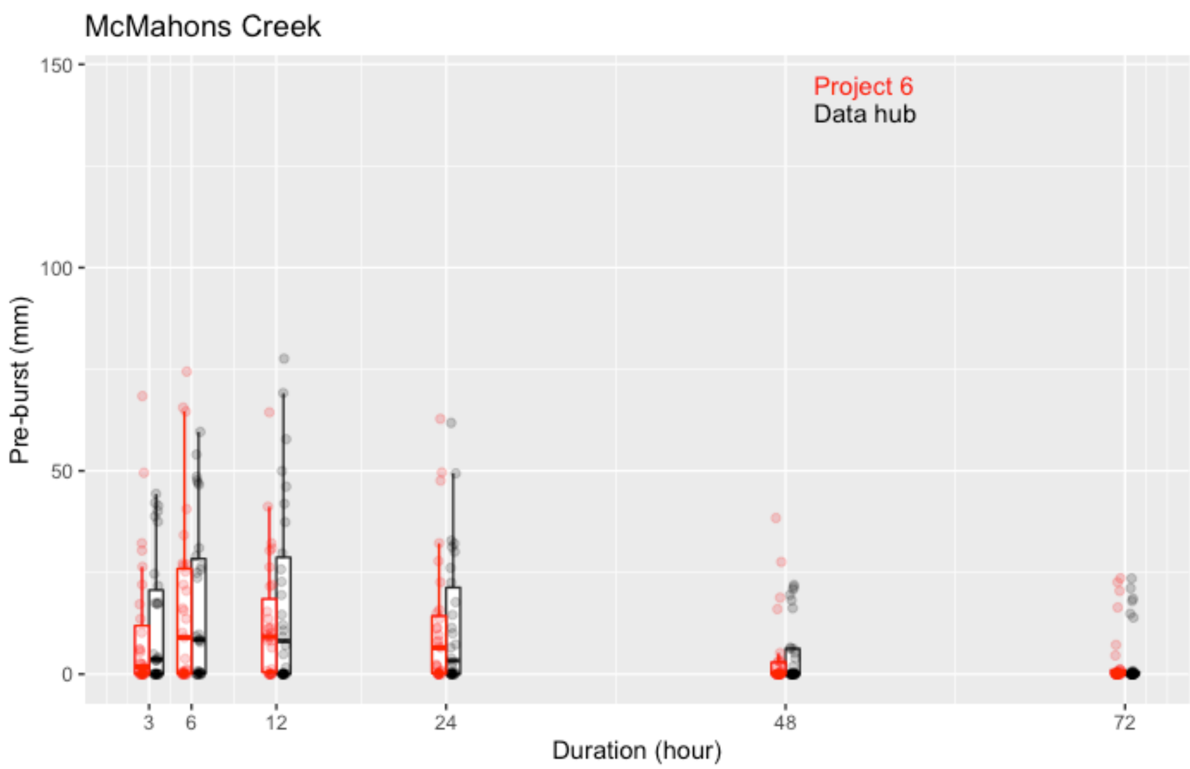

Figure 19: McMahons Creek: comparison of pre-burst values from Project 6 and the data hub

Figure 20: Tarago River: comparison of pre-burst values from Project 6 and the data hub

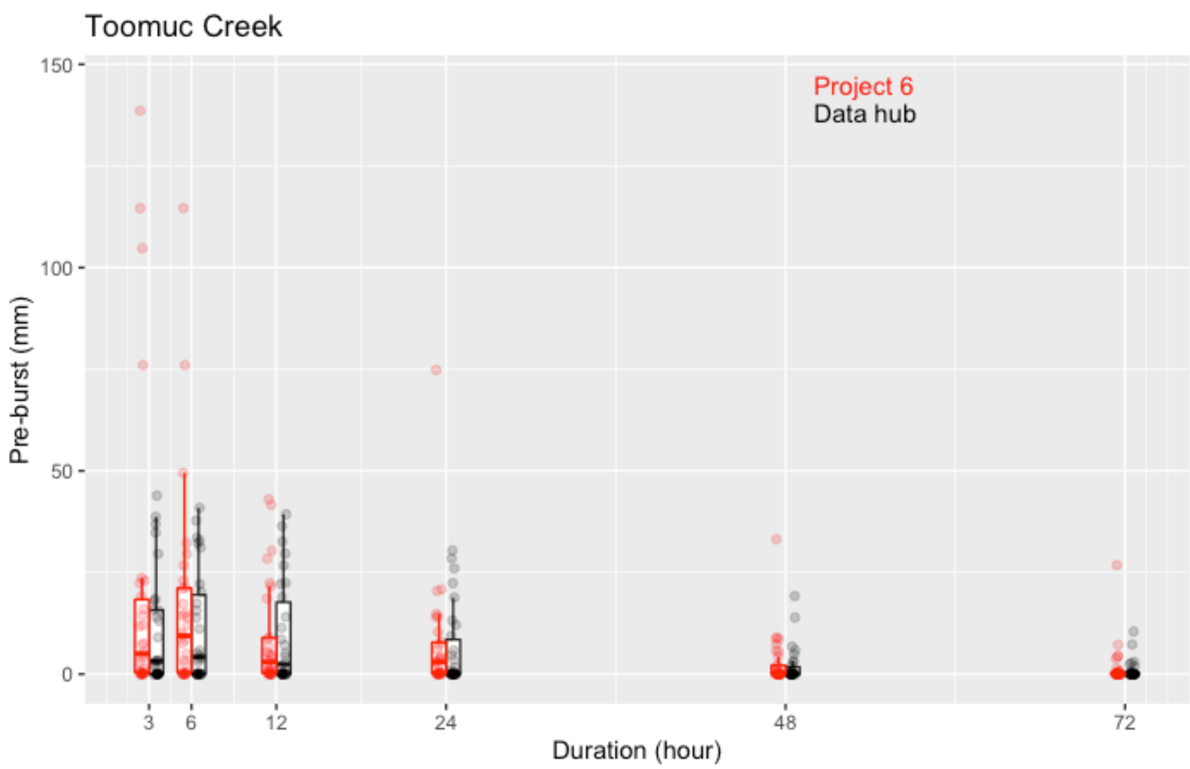

Figure 21: Toomuc Creek: comparison of pre-burst values from Project 6 and the data hub

4. Pre-burst for burst durations less than 60 min

Pre-burst rainfall for durations less than 60 min is an important input to modelling for small catchments, particularly with urban land use. This data is not available from the ARR data hub. This section:

- documents the available data on pre-burst rainfall associated with short duration bursts
- outlines an approach to provide consistent and reliable data.

4.1. Pre-burst rainfalls for short duration bursts

Pre-burst rainfalls for events shorter than 60 min are required in modelling. Currently, these are estimated using two pragmatic approaches.

- extrapolating pre-burst values from bursts 60 min or longer
- holding pre-burst constant at the 60 min values for burst shorter than 60 min.

There is little justification for either of these approaches. Extrapolation is challenging because there is not a smooth relationship between pre-burst rainfall and burst duration (Figure 6 and Figure 7). There is also very limited data that justifies holding pre-burst constant (see below).

4.2. Literature data on pre-burst associated with short duration bursts

The only data available in the pre-burst literature related to short duration bursts, is provided by Srikanthan and Kennedy (1991) (Appendix B). They included an analysis of pre-burst rainfalls for

Melbourne and Brisbane for burst durations of 15 min, 30 min and longer, with antecedent periods that included 15 min, 30 min and 360 min (Table 7).

The change in pre-burst rainfall with burst duration, for 1 hour and 6 hour antecedent periods, is shown in Figure 22. The 6 hour antecedent period is of most relevance and this shows reasonably constant pre-burst rainfall as burst duration decreases. Although these data are very limited, only applying to a single location, they have been taken to justify using the 60 min pre-burst values from the data hub for burst durations shorter than 60 min.

Table 7: Median pre-burst rainfall (mm) for short duration bursts (Srikanthan and Kennedy, 1991)

Burst duration (min)	Pre-burst period				
	15 (min)	30 (min)	60 (min)	6 (hour)	24 (hour)
15	1.6		2.6	4.3	
30		0.9	1.2	3.7	
60			1.1	4.5	5.3

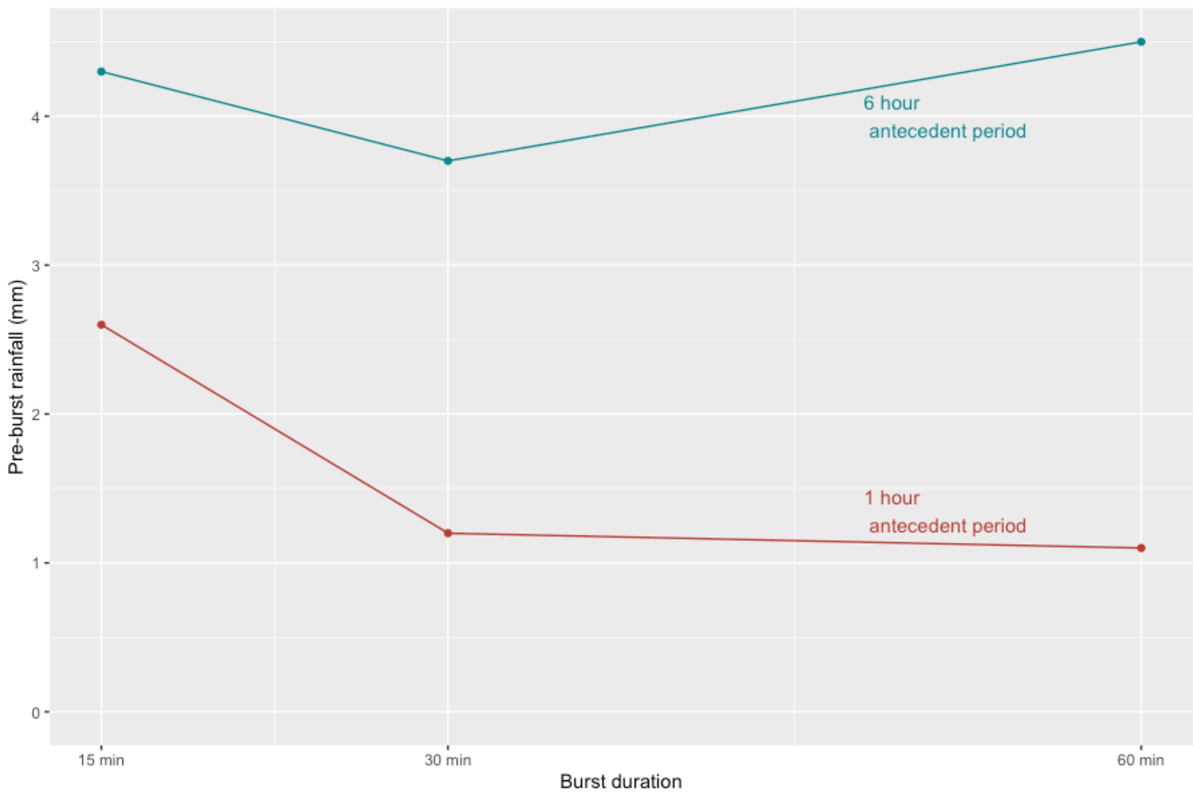

Figure 22: Short duration pre-burst values for 30 min and 60 min antecedent periods (Srikanthan and Kennedy, 1991)

4.3. Short duration pre-burst values from Project 3

As discussed in Section 2, pre-burst information from Project 3 was obtained from analyzing storms from the national storm database. These events are characterised by critical rainfall burst. The published pre-burst information, available from the data hub, uses a minimum burst duration of 60 min, however, according to the Project 3 documentation, storms with critical bursts of 5, 10, 15 and 30 min were also collected (Table 1) (Loveridge, 2015b; Loveridge pers. comm.). It is likely that there are many storms with significant short duration bursts because they were used to define temporal patterns which require at least 30 storms for each burst duration of 10, 15, 20, 25, 30, 45 and 60 min. Further information on the national storm database has been sought from WMA Water.

4.4. Short duration pre-burst values from ARR Project 6

Multiple burst durations were considered in Project 6 with the shortest being 3 hours. For each burst duration, a set of storm events was identified that included significant rainfall for the chosen bursts. Across the full set of durations, about 100 complete storm events were identified at each site.

A similar process could be used to identify storms appropriate for shorter duration bursts. That is, the procedure listed in Section 3.2 could be followed. This would require a substantial amount of work which may not be warranted given that the national storm database has since been established.

As an interim measure, the existing set of complete storm events were analysed to determine if they contained significant short duration bursts. An AEP of 50% was used as a threshold. Pre-burst rainfalls were identified where the complete storms contained these bursts.

Results showed that at the Project 6 Victorian sites, the pre-burst ratio increased as the burst duration decreased below about 3 hours. A typical result is shown in Figure 23 for the Aire River. This shows the individual data points which represent changing ratios as event-based windows expand with increasing burst duration, along with a smooth regression line trending upward for shorter duration bursts. There was a similar result for pre-burst depth which increased, as burst duration decreased, for the Axe, McMahons, and Tarago catchments. It remained constant for the Aire River and there was insufficient data to determine a relationship for Toomuc Creek. These results call into question the assumption of constant pre-burst depths and ratios for burst durations shorter than 60 min.

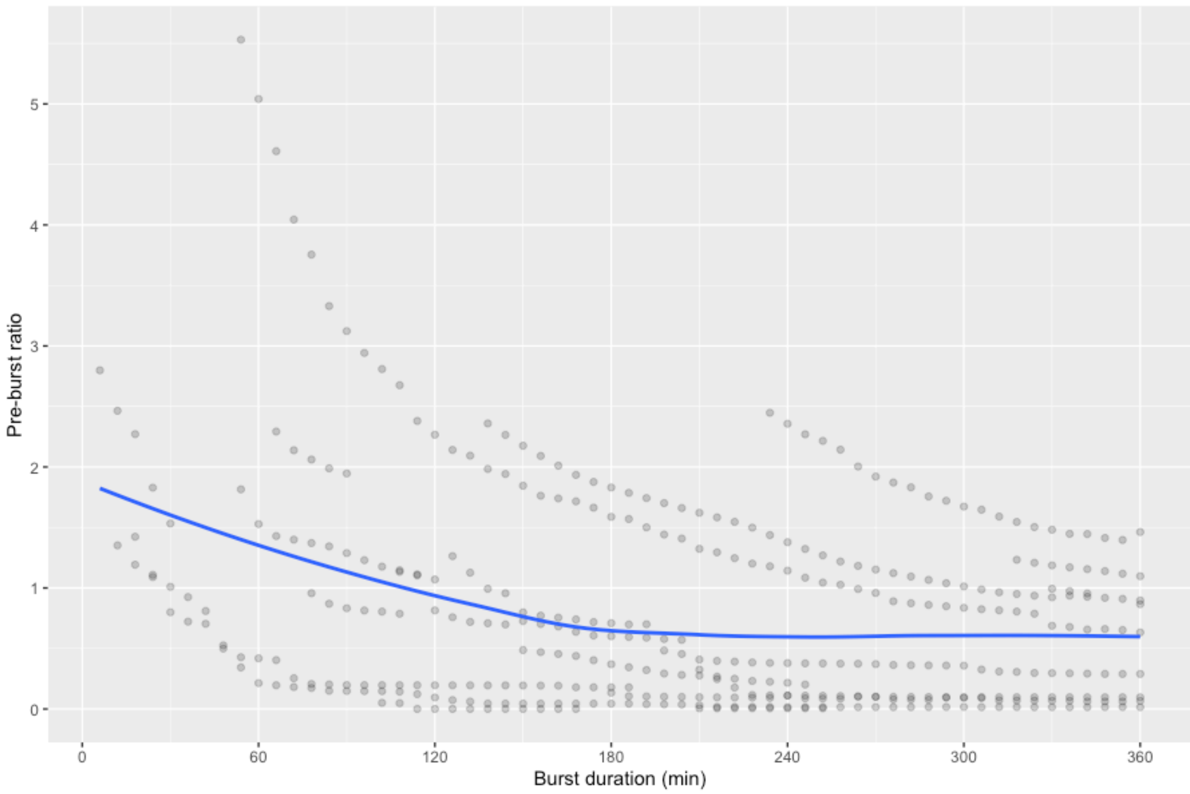

Figure 23: Pre-bursts ratio as function of burst duration (Aire River)

4.5. Further work

To progress the development of guidance for pre-burst rainfall for short duration bursts, the following steps are recommended:

- Partner with the Bureau of Meteorology to obtained access to the quality controlled pluviograph database. This contains 2280 stations with more that 8 station years of data including 754 stations owned by the BoM and 1526 owned by other data agencies throughout Australia (Green et al, 2011). Victorian sites represent a subset of the this database.
- Work with WMA Water to obtain access to relevant events in the national storm database. This includes storms within Victoria and nearby sites in NSW and South Australia.
- Review the data provided by the national storm database to determine:
    - If there are an adequate number of events with short duration bursts
    - If the event data can be processed to determine pre-burst values that are consistent with the methods used in project 6
    - If a procedure can be developed to provide reliable pre-burst values for coastal areas i.e. if the problem of extrapolating from drier inland areas can be overcome.
- Supplement the national storm database with additional pluviograph data if required, depending on the review
- Process the storm event data to determine the pre-bursts for storms with short duration bursts
- Extrapolate to provide a grid of values throughout Victoria.

It would be beneficial to undertake this work as part of a broader review of pre-burst data.

5. Conclusion

This report has identified a series of issues with the pre-burst data, procedures and guidance provided by Australian Rainfall and Runoff. Some of these are recognised within ARR[9] where the potential for bias is acknowledged, along with a commitment to update the pre-burst analysis to reflect the latest IFD values. The necessity for this update remains, which would also provide an opportunity to address other concerns.

A key issue relates to the consistency in the way rainfall is analysed in the losses project (Project 6) compared to the project that derived the pre-burst values (Project 3). A comparison at 5 locations in Victoria, suggests that, as an interim measure, the pre-burst values from the data hub can be used in modelling, along with the ARR losses. However there are likely to be problems in some areas that can only be addressed as part of a larger pre-burst project.

The lack of pre-burst information for short duration events is also an important shortcoming. A project is outlined to address this gap which builds on work by the Bureau of Meteorology to create a quality controlled set of pluviograph data, and work by WMA Water to create a national storm database.

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[9] ARR Book 2, Chapter 5.4:

The pre-burst was characterised based on the rarest rainfall duration burst within the storm using the 2013 IFDs. Hill et al. (2015) found this approach gave a biased estimate of the average pre-burst, systematically underestimating the depth of the pre-burst. Following from this work and the expected update of the IFDs from the Bureau of Meteorology in 2016 this work will be updated…

6. References

Farnsworth, N., Turner, L., & Pearce, H. (1996). Analysis of antecedent and subsequent rainfall. *23rd Hydrology and Water Resources Symposium*, (21-24 May), 433–438.

Green, J; Xuereb, K & Siriwardena, L 2011. Establishment of a Quality Controlled Rainfall Database for the Revision of the Intensity-frequency-duration (IFD) Estimates for Australia. In: Proceedings of the 34th World Congress of the International Association for Hydro-Environment Research and Engineering, 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering. Engineers Australia, 2011: 154-161. ISBN: 9780858258686. Barton, ACT.

Hill, P., Graszkiewicz, Z., Loveridge, M., Nathan, R., & Scorah, M. (2015). Analysis of loss values for Australian rural catchments to underpin ARR guidance. *Hydrology and Water Resources Symposium*. https://doi.org/10.1017/CBO9781107415324.004

Hill, P., Graszkiewicz, Z., Taylor, M. and Nathan. R. (2014) Analysis of loss values for rural catchments across Australia. Australian Rainfall and Runoff Revision Project 6 – loss models for catchment simulation. Engineers Australia.

Hill, P., Zhang, J. and Nathan, R. (2016) Australian Rainfall and Runoff Revision Project 6 – loss models for catchment simulation. Stage 3 report. Engineers Australia.

Jordan, P., Nathan, R., Mittiga, L., & Taylor, B. (2005). Growth curves and temporal patterns of short duration design storms for extreme events. *Australian Journal of Water Resources*, *9*(1), 69–80.

D. Kahle and H. Wickham (2013). ggmap: Spatial Visualization with ggplot2. The R Journal, 5(1), 144-161. URL http://journal.r-project.org/archive/2013-1/kahle-wickham.pdf

Loveridge, M., Babister, M., Stensmyr, P., & Adam, M. (2015a). Estimation of pre-burst rainfalls for design flood estimation in Australia. 35th Hydrology and Water Resources Symposium, (December 2015)

Loveridge, M., Stensmyr, P. and Babister, M. (2015b) Australian Rainfall and Runoff. Project 3, Temporal Patterns of Rainfall. Part 1 – Development of an event database.

Loveridge, M., Stensmyr, P. and Babister, M. (2015c) Australian Rainfall and Runoff. Project 3, Temporal Patterns of Rainfall. Part 2 – Pre-burst rainfall May 2015.

Minty, L. J., Meighen, J. and Kennedy, M. R. (1996) Development of the Generalised Southeast Australia Method for Estimating the Probable Maximum Precipitation, HRS Report No., 4, Hydrology Report Series, Bureau of Meteorology, Melbourne, Australia, August 1996, 48 pages.

Minty, L., & Meighen, J. (1999). *Rainfall Antecedent To Large and Extreme Rainfall Bursts Large and Extreme Rainfall Bursts*. Water 99 Joint Congress. Brisbane Australia 6-8 July 1999

Pilgrim, D. H., & Cordery, I. (1975). Rainfall temporal patterns for design floods. *Journal of the Hydraulics Division American Society of Civil Engineers*, *101*(HY1), 81–95. https://doi.org/10.1353/man.2000.0052

Scorah, M., Hill, P., & Nathan, R. and Graszkiewicz, Z (2015). *Outcomes from a pilot study to investigate pre-burst rainfall depths for Australian catchments*. 35th Hydrology and Water Resources Symposium, (December 2015)

Srikanthan, R., & Kennedy, M. R. (1991). *Rainfall Antecedent to Storm Bursts from which Temporal Patterns Were Derived* (pp. 280–282). pp. 280–282.

Stensmyr, P., Loveridge, M. and Babister, M. (2015) Australian Rainfall and Runoff – Project 3: Temporal patterns of Rainfall, Part 1 – Development of an event database. The Institution of Engineers, Australia. Canberra.

WMA Water (2019) Review of ARR design inputs for NSW. Office of Environment and Heritage. https://www.environment.nsw.gov.au/research-and-publications/publications-search/review-of-australian-rainfall-and-runoff-design-inputs-for-nsw (accessed 19 March 2020)

Appendix A: Burst initial loss calculations

A.1 Introduction and summary

Burst initial loss refers to the rainfall (mm) that is either added to, or subtracted from, the burst obtained from IFD data. Burst initial loss can be either positive or negative. A positive initial loss reduces the burst depth, a negative initial loss increases it (ARR2019, Book 2, Chapter 5.9.9).

There are at least four methods that are currently being used to calculate burst initial loss. In all cases, burst initial loss is a function of two quantities; storm initial loss and pre-burst rainfall. The methods differ in how they account for the variability of these quantities. This memo outlines the methods and applies them to Toomuc Creek as a case study.

Findings of the case study are summarised as follows:

- Pre-burst depth is highly variable. The range of pre-burst depths in the case study varies from 0 times the median pre-burst depth to 60 times the median pre-burst depth. In contrast, storm initial loss varies between 0.14 times and 3.19 times the median storm initial loss. The distribution of pre-burst rainfall is also highly skewed with many zero values and a few large values.
- In the case study, the range of pre-burst values is smaller than the range of storm initial loss values. Pre-burst varies from 0 to 30 mm, while storm initial loss varies from 3.5 to 79.8 mm.
- Taking burst initial loss (IL_b) as storm initial loss (IL_s), less pre-burst rainfall (PB) i.e.

  $IL_b = IL_s - PB$,

  means that, for the case study, if the full distribution of IL_s and PB are considered, IL_b will range from 79.8 mm (for the high storm initial loss, low pre-burst case) to -26.5 mm (for the low initial loss, high pre-burst case). That is, the rainfall taken forward for modelling could be 26.5 mm greater than the burst rainfall.
- The Monte-Carlo procedure in RORB samples from the storm initial loss but holds the pre-burst fixed at the median value. In the case study, the median pre-burst value is 0.5 mm, so using the RORB approach, burst initial loss will range from 79.3 mm to 3 mm, that is, always positive so always reducing burst rainfall. This is substantially different to the 26.5 mm that could be added to burst rainfall if the full pre-burst distribution was sampled.
- There are "probability neutral burst initial loss" values provided on the data hub for NSW locations and a recommendation that these should be used by practitioners. It is not yet clear how these were calculated or how they should be used in modelling. These new burst initial loss values may cause a step change in modelling results at the Victorian/NSW border.

A1.1 Calculating burst initial loss

Four methods have been proposed to calculate burst initial loss:

1. Burst initial loss based on median values of storm initial loss and pre-burst rainfall

   $median(IL_b) = median(IL_s) - median(PB)$

   This is the standard approach recommended in ARR2019 and on the data hub for all states except NSW. The median values of storm initial loss, and burst initial loss, are available from the data hub.
2. Burst initial loss based on median pre-burst but using the full distribution of storm initial loss values

   $IL_b = ILs - median(PB)$

   This is the approach used in RORB when the distribution of storm initial loss is sampled.
3. Burst initial loss based on distribution of storm initial loss values and pre-burst values. This produces the distribution of burst initial loss values.

   $IL_b = ILs - PB$
4. Probability neutral value of IL_b

   The "Probability neutral" approach to estimating burst initial loss is discussed in WMA Water (2019, Section 7, p20). Steps are explained below.

A.2 Case study

A2.1 Introduction

The different calculation methods are explored for a case study as follows.

- Toomuc Creek at Pakenham
- Catchment centroid: Lat = -38.064520, Lon = 145.463277
- Duration = 1080 min = 18 hours
- AEP = 20%

A2.2 Data hub information

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Storm initial loss = 25.0 (this is the median value of storm initial loss)

Storm continuing loss = 4.4

Pre-burst information is provided in Table A1.

IFD data: the 18 hour, 20% AEP event has a rainfall depth of 63.6 mm and an intensity of 3.54 mm/h.

Table A1: Pre-burst information for Toomuc Creek, duration = 1080 min, AEP = 20%

Percentile	Pre-bust depth (mm)	Pre-bust ratio
10	0	0
25	0	0
50 (median)	0.5	0.008
75	7.6	0.12
90	21.2	0.333

A2.3 Distribution of storm initial loss

Standardised loss factors are provided in ARR 2019 Book 5, Chapter 3 Table 5.3.13 (Table A2). The storm initial loss percentiles for the case study can be calculated by multiplying the standardised ILs values by the median storm initial loss (25 mm in this case).

Table A2: Initial loss distribution (source ARR 2019 Book 5, Chapter 3 Table 5.3.13)

Percentile	Standardised ILs	ILs percentiles for the case study (mm)[10][1]
0	3.19	79.75
10	2.26	56.5
20	1.71	42.75
30	1.4	35
40	1.2	30
50	1.0	25
60	0.85	21.25
70	0.68	17
80	0.53	13.25
90	0.39	9.75
100	0.14	3.5

The percentiles can be used to randomly generate appropriately distributed loss values using the methods in ARR Book 4. An example is provided in Figure A1 which shows percentiles calculated from 500 randomly generated values compared to the percentiles from Table A2. The empirical percentiles closely approximate the standard values; the approximation improves as the number of sample points increases. This provides confidence that the generated storm initial loss values match the specified distribution.

[10] Initial loss percentiles are 25 times the standardised ILs values (the median storm initial loss, from the data hub, is 25 mm)

An alternative way of looking at the data is as a histogram Figure A2. This has been generated from 10,000 random storm initial loss values. The median of the random values is 25.2 mm, close to the expected median of 25 mm.

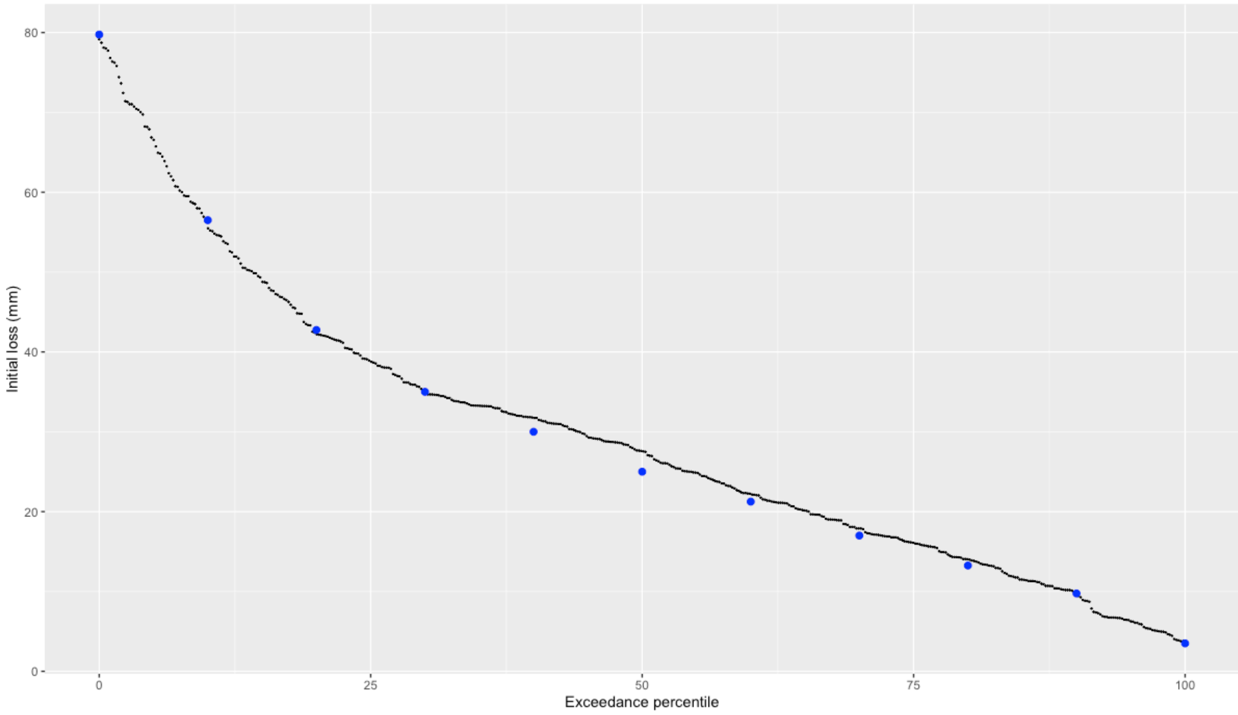


Figure A1: Distribution of storm initial loss for the case study. Blue points show values from Table , black points show the percentiles of 500 randomly generated initial loss values.

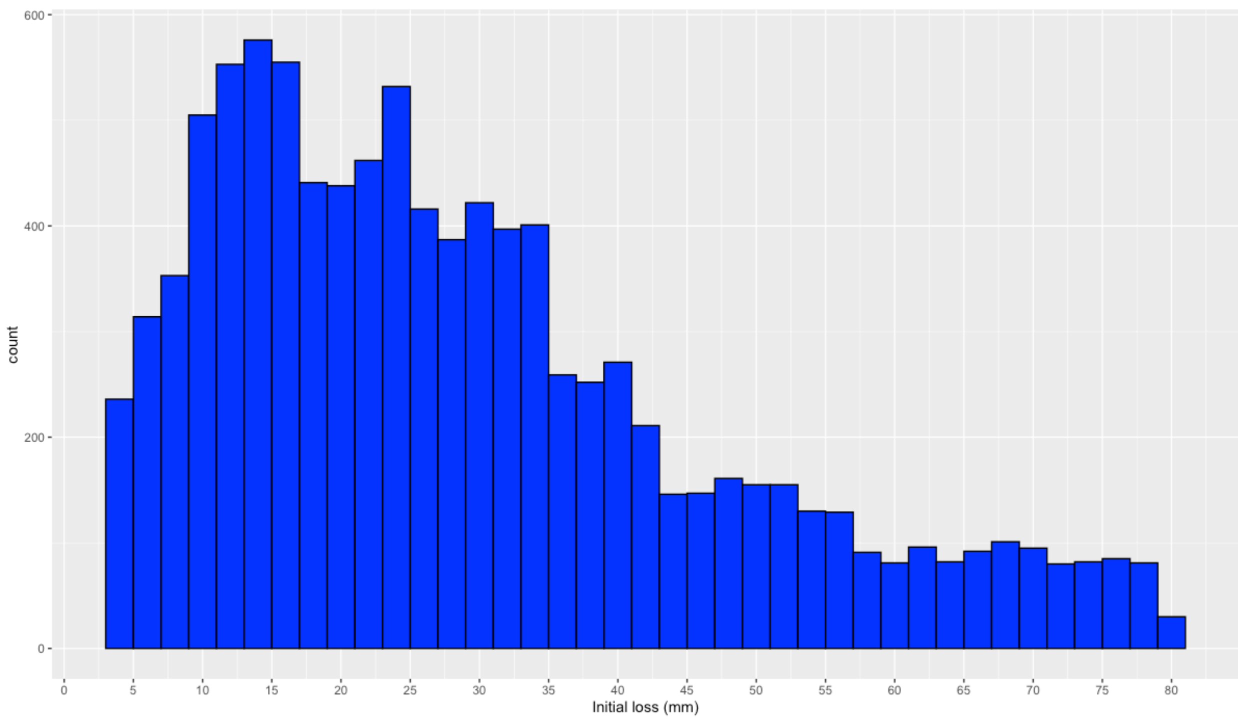


Figure A2: Histogram based on 10,000 random storm initial loss values

A2.4 Distribution of Pre-burst rainfall

The percentiles in Table A1 can be used to generate pre-burst values using the same method as for initial loss.

There are two issues:

- Percentiles are only available for 5 values (10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th}). Interpolation can be used to estimate pre-burst values between these percentiles, but it is also necessary to have estimates of pre-burst for the 0^{th} and 100^{th} percentile. These were estimated by extrapolation. The zeroth percentile pre-burst is assumed to be 0 mm, the 100^{th} percentile pre-burst is estimated to be 30.3 mm.
- The percentiles are defined such that a large percentile corresponds to a large value of pre-burst rainfall; this is the opposite to the exceedance percentiles used to define the distribution of storm initial loss. This is easily addressed but it is important to ensure the generated values are appropriate.

Exceedance percentiles and the corresponding pre-burst values are shown in Figure A3. A histogram of generated pre-burst values is shown in Figure A4.

The median of these values is 0.495, close to the expected value of 0.5. About half of the generated values are less than 0.5. There are a few values up to 30 mm.

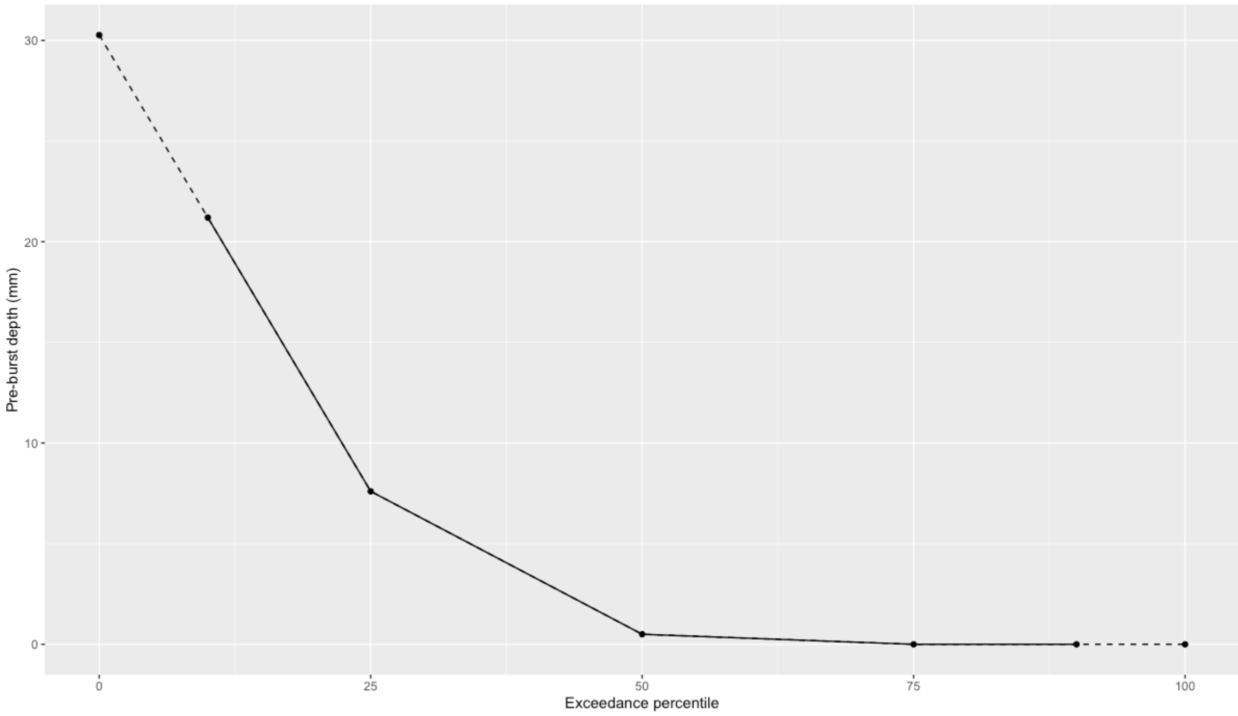


Figure A3: Exceedance percentiles and corresponding pre-burst values. Extrapolated values are dashed

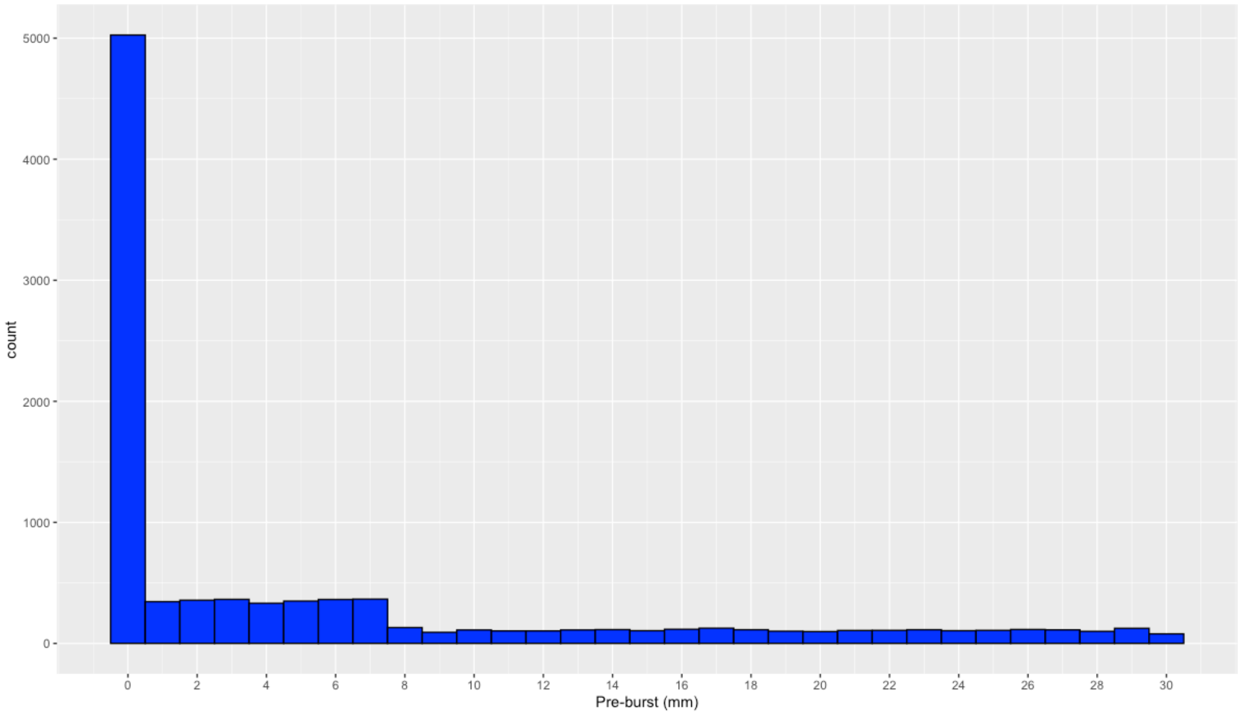


Figure A4: Histogram of 10,000 randomly generated pre-burst values

A2.5 Calculations

Method 1

Adopt the data hub values for median IL_s and median pre-burst.

$$median(IL_b) = median(IL_s) - median(PB)$$

$$= 25 - 0.5 = 24.5 \text{ mm}$$

Median pre-burst = 24.5 mm

Method 2

$$IL_b = ILs - median(PB)$$

For this approach, a large number of random samples were generated for storm initial loss based on the percentiles in Table A2. These are used to determine the histogram of storm initial loss values shown in Figure A4.

Median(ILb) = 24.72 mm

Note that median IL_b for this method is larger than for method 1.

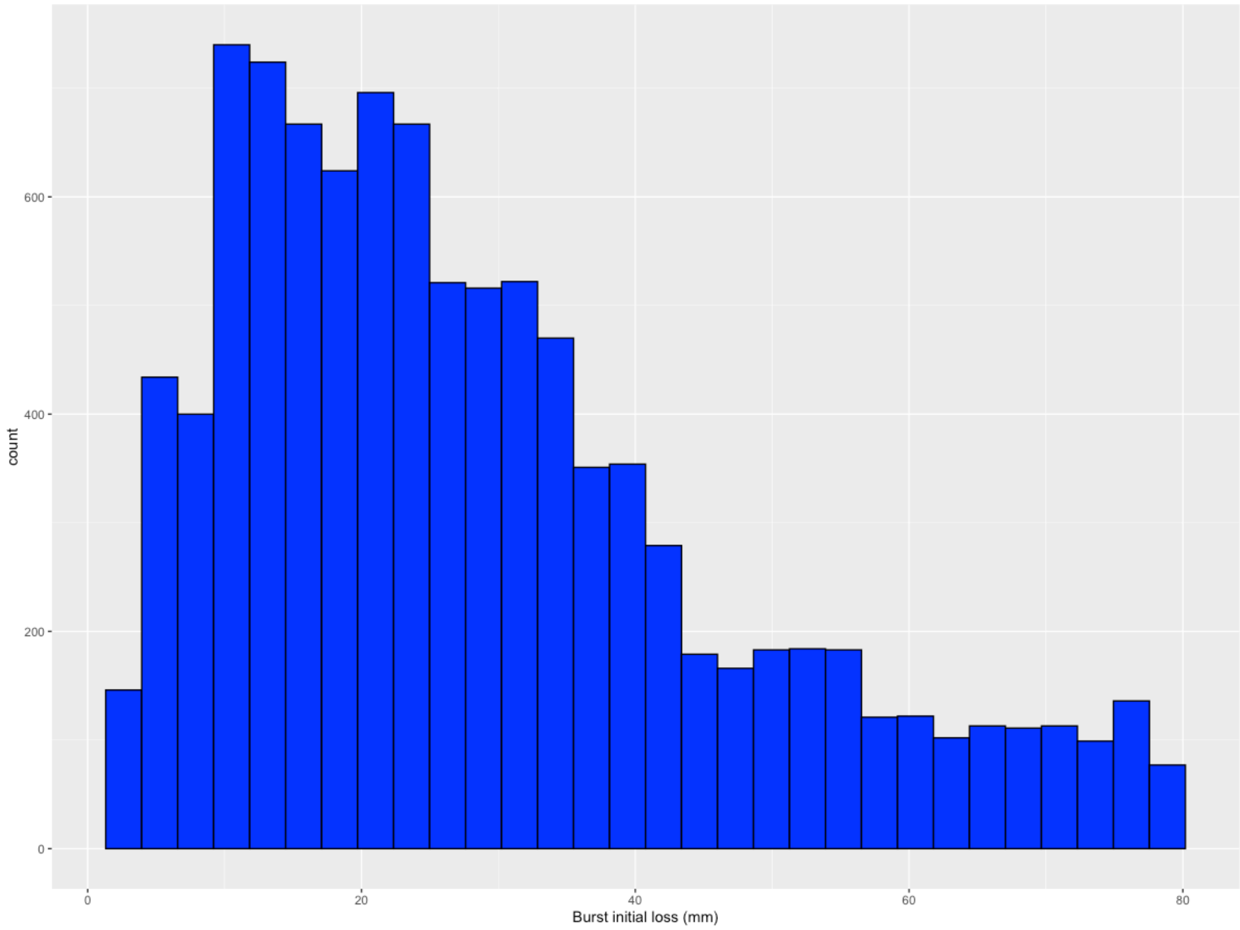


Figure A5: Histogram of burst initial loss values using Method 2 (N = 10000)

Method 3

Using the 10000 randomly generated values for ILs and pre-burst.

IL_b= ILs –PB

median(IL_b) = 20.5 mm

Note that this is substantially less than the initial loss for Methods 1 and 2.

The distribution of Method 2 IL_b values is shown in Figure A6.

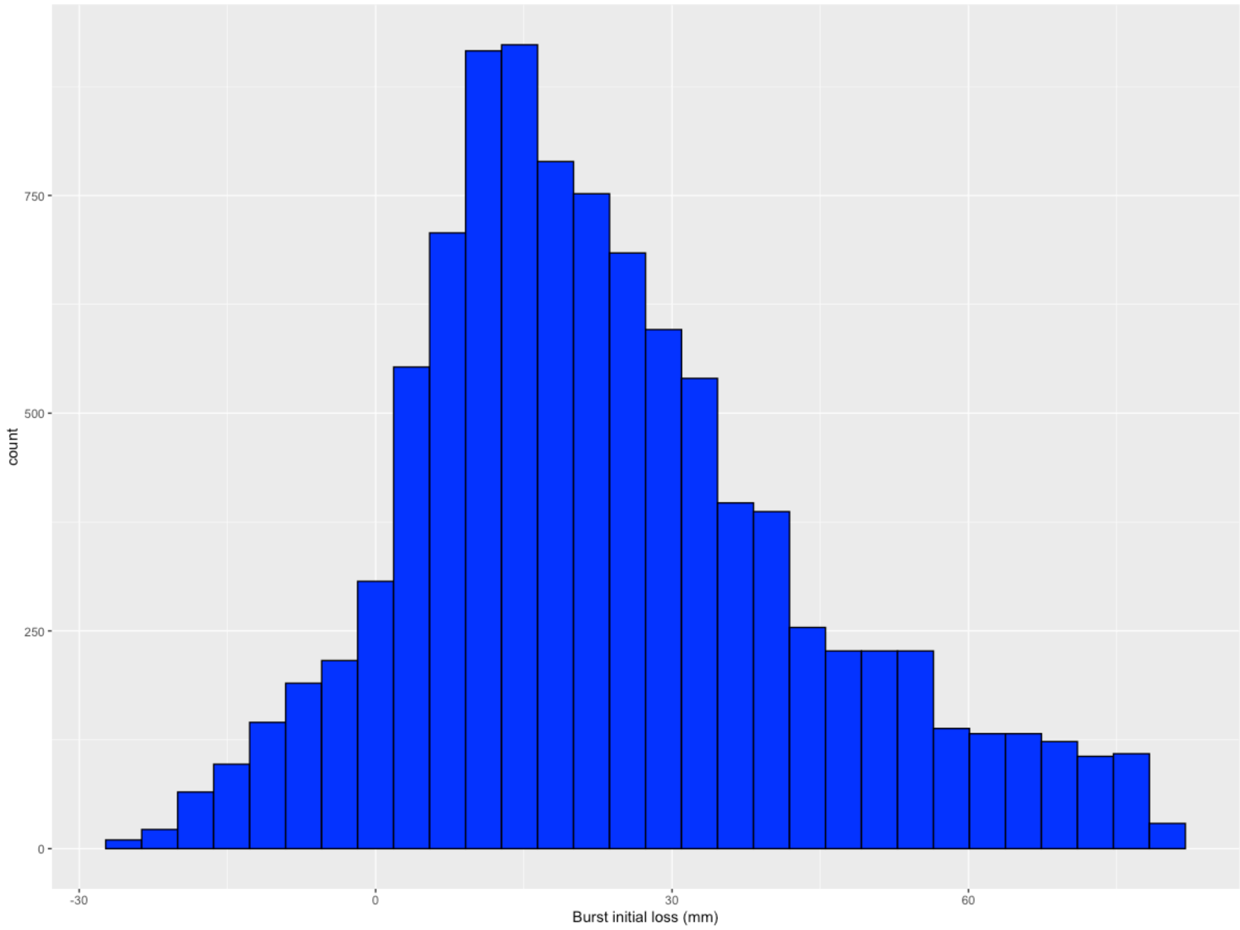


Figure A6: Histogram of burst initial loss values using Method 3 (N = 10000)

Method 4

Method 4, the produces the probability neutral burst initial loss values which are now available from the data hub for NSW. Unfortunately, this method has not been well documented with some information available from WMA Water (2019, Section 7).

1. Choose a location, duration and AEP of interest: e.g. Toomuc Creek at Pakenham, duration = 1080 min (18 hours), AEP = 20%,
2. Randomly generate 5000 numbers between 0 and 1 from the uniform distribution
3. Treat these as AEP values
4. Determine the rainfall depth for each of these AEP values using IFD2016 relationship for the chosen location and duration
5. Sample 5000 initial loss values (ILs) using the percentile data from Table 5.3.13 in ARR2019
6. Sample 5000 pre-burst values for the AEP and duration of interest (PB)
7. Calculate ILs - PB (there will be 5000 values) and set any values less than zero to zero
8. Calculate "rainfall after initial loss satisfied" = rainfall from step 4 - the value from step 7, set any values less than zero to zero
9. Calculate the difference between rainfall from step 4 and the value of "rainfall after initial loss satisfied" from step 8.

10. The median of the 5000 values from step 9 is the probability neutral burst initial loss.

Using this procedure the burst initial loss for the case study is 19.97 ~ 20 mm.

This approach has been tested by attempting to reconcile the "probability neutral burst initial losses" at NSW locations on the data hub. The answers are close, but not the same and it is not clear what the issue is. Advice has been sought from WMA Water.

A.3 Comparisons

Section A.2 provided a worked example for a single value of AEP and duration. Results are summarised in Table A3. A comparison of methods is also shown Figures A7 and A8. The results from Method 1 and 2 are similar, and are substantially larger than Method 3. Note the negative initial loss values for Method 3. These negative values are equivalent to adding rainfall, sometimes a substantial amount, to the burst, even after initial loss is satisfied. Method 4 has not been explored further at this stage until feedback is received from WMA Water.

The case study used a single AEP-duration combination. Results for all available AEP and duration combinations are shown in Figures A9 and A10 for the case study location. These two figures present the same information but presented in different ways. Figure A9 plots IL_b against AEP with panels showing duration while Figure A10 shows a plot against duration with panels showing AEP. These confirm that the results for Method 1 and 2 are similar but results for Method 3 are consistently smaller across all AEPs and particularly for smaller durations.

This raises the question of whether the method used by RORB, Method 2, is providing burst initial loss values are consistently biased high because the variation in pre-burst is ignored.

A preliminary recommendation is that method 3 is likely to be the most technically correct. However this is subject to caveats. First, this method has not been implemented in any software. Second, we need to be sure that the ultimate outcome, the flood peaks are unbiassed when considering all inputs and processes. This would need to be tested by comparing a modelled flood frequency relationship with that determined from gauged data using similar approaches to that in the main report.

Table A3: Median burst initial loss values for the 4 methods

Method	Method	Median Burst Initial Loss (mm)
1	$\text{median}(IL_b) = \text{median}(IL_s) - \text{median}(PB)$	24.5
2	$\text{median}(IL_b) = \text{median}(ILs - \text{median}(PB))$	24.7
3	$\text{median}(IL_b) = \text{median}(ILs - PB)$	20.5
4	WMA Water method	20.0

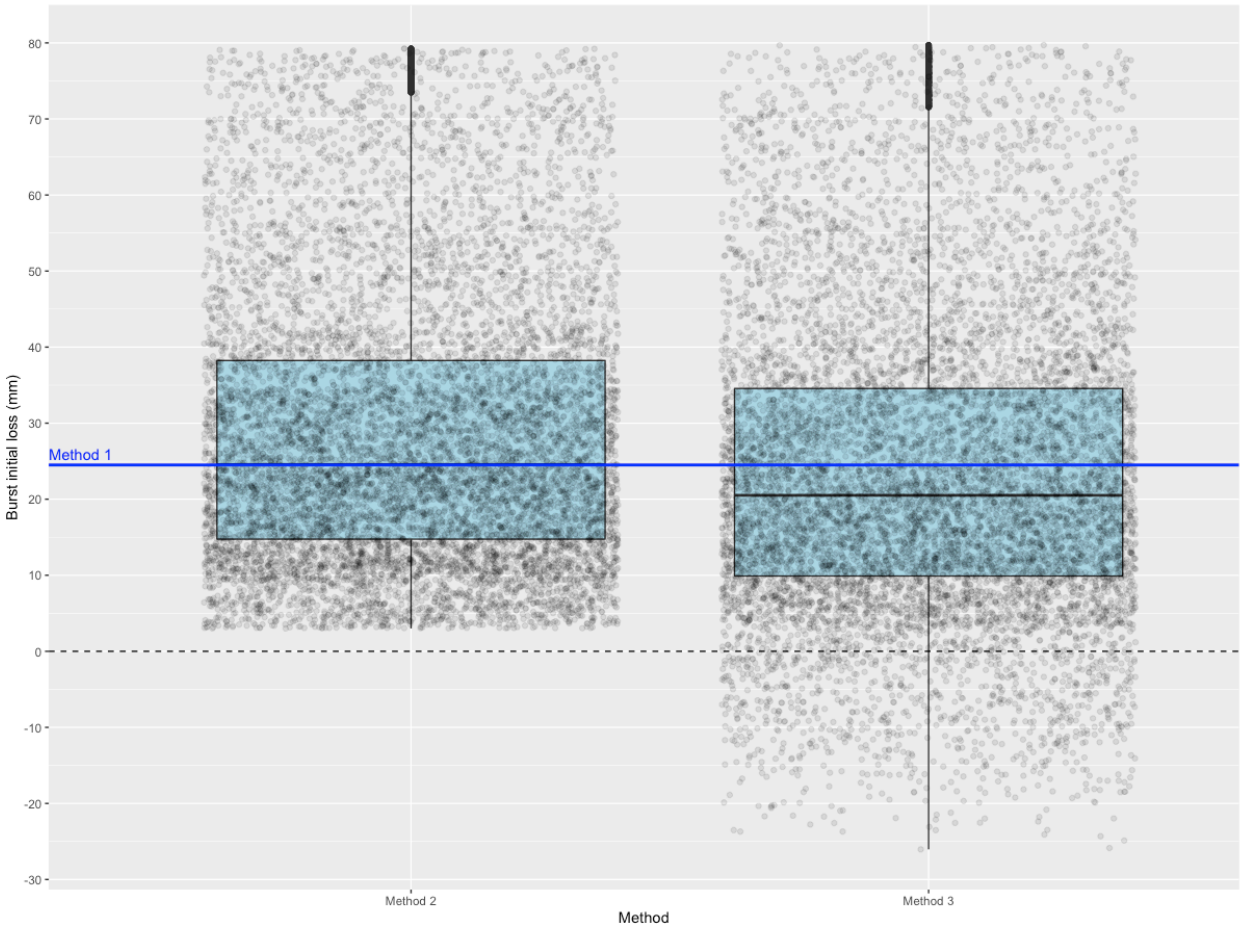


Figure A7: Comparison of burst initial loss values calculated using the three methods

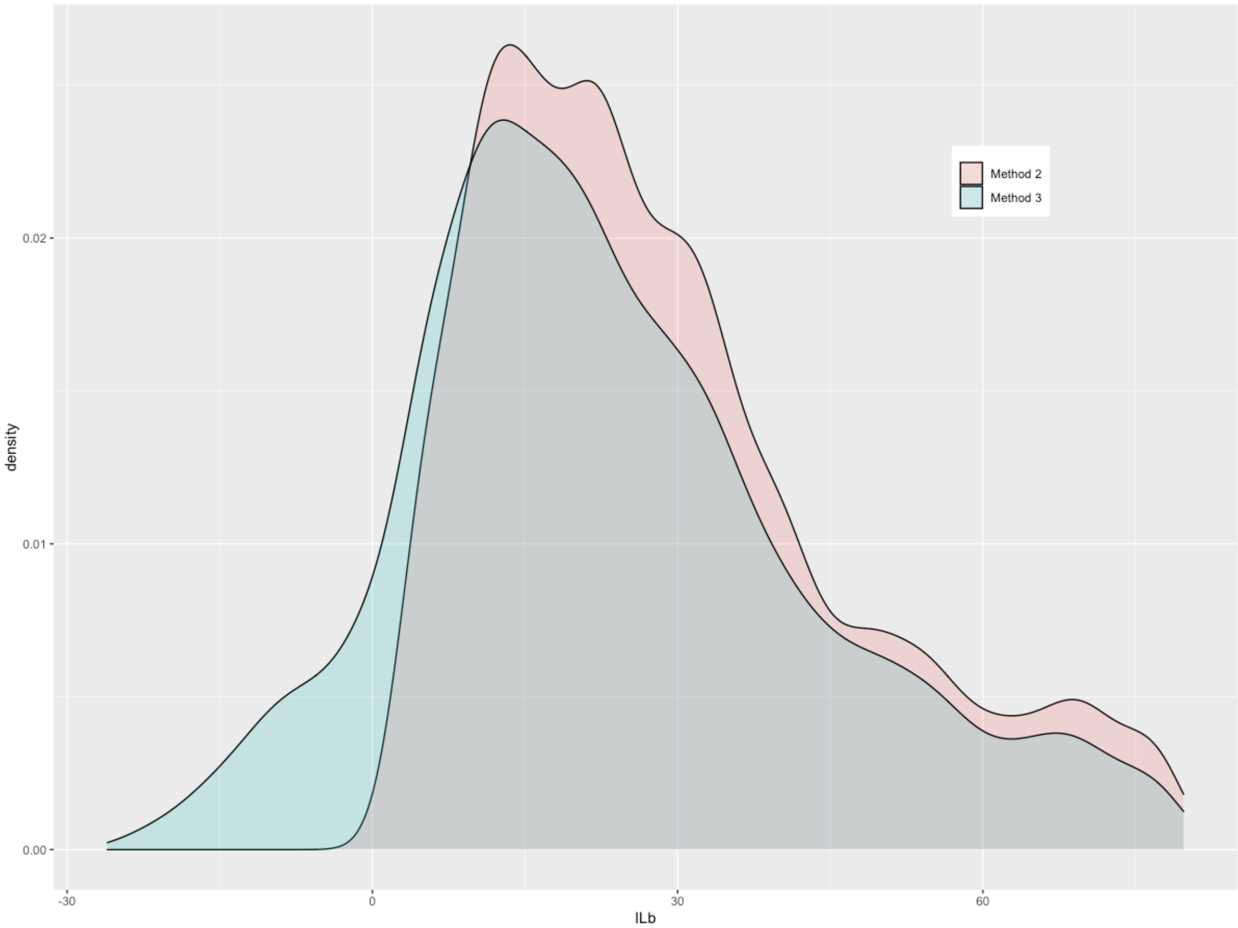


Figure A8: Comparison of Methods 2 and 3 as a density plot

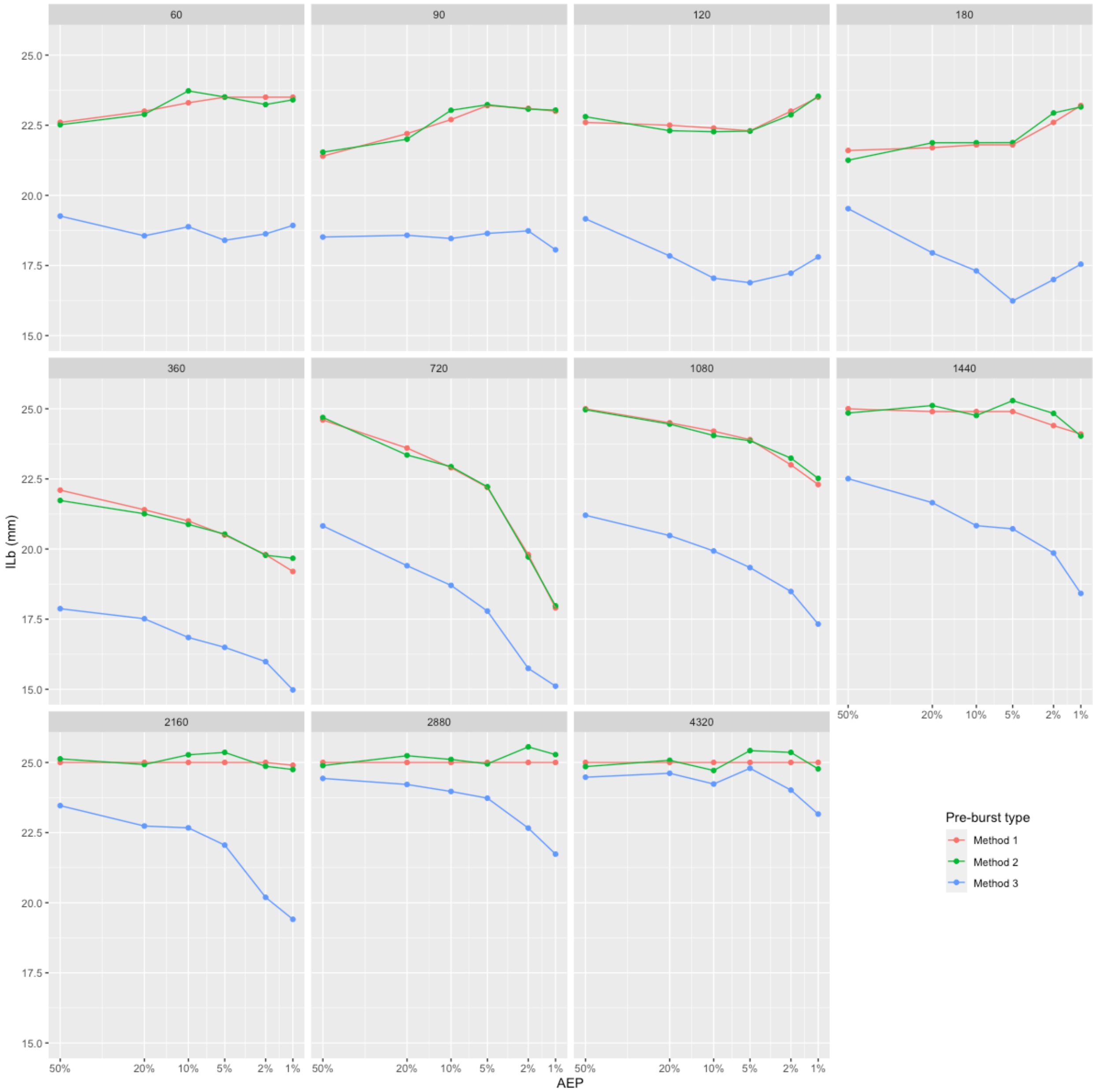


Figure A9: Median burst initial loss comparison; panels show burst duration in minutes. Median storm initial loss is 25 mm

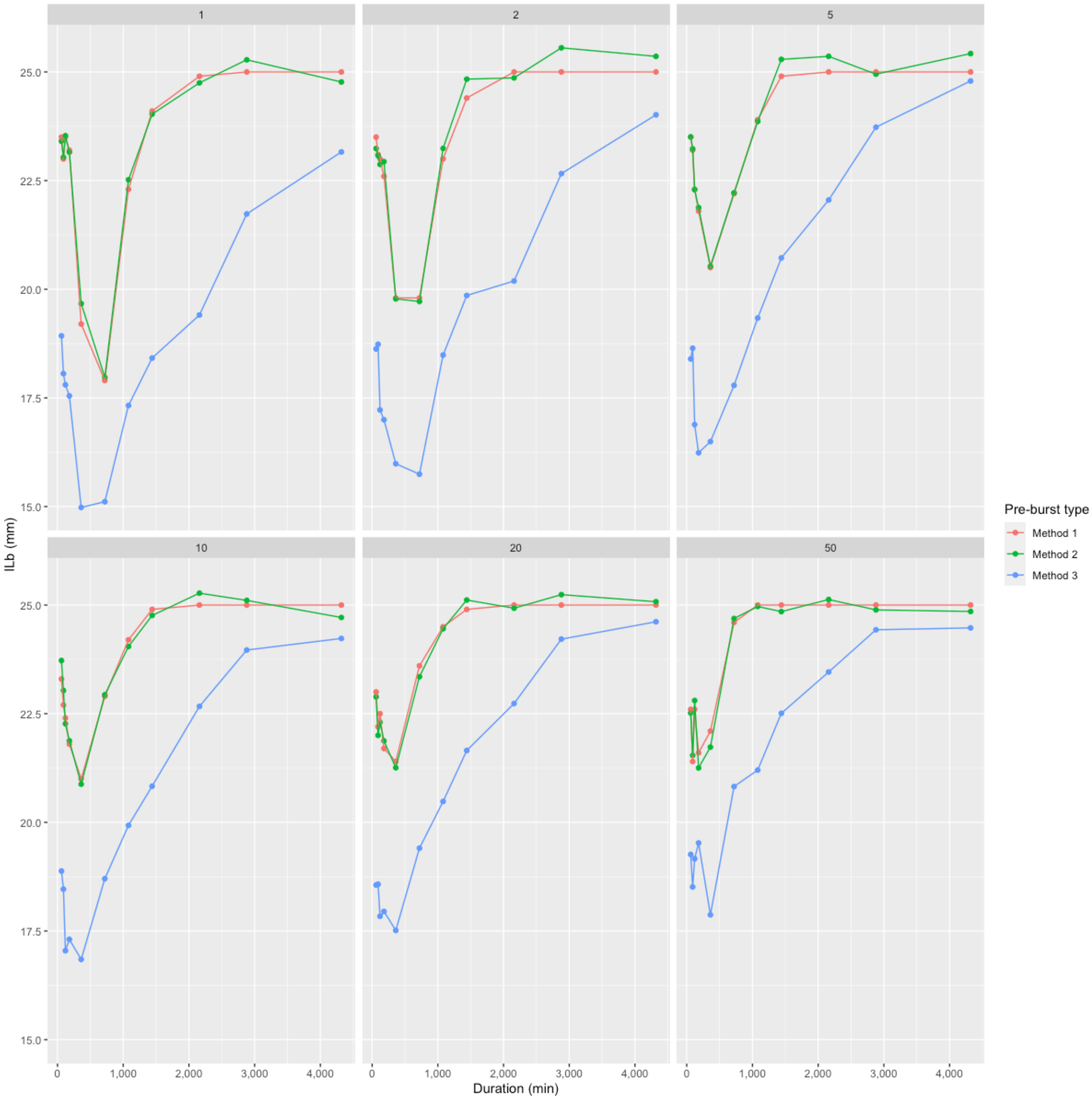


Figure A10: Median burst initial loss comparison; panels show AEP (%). Median storm initial loss is 25 mm

Appendix B: Alternative pre-burst estimates

Pre-burst is not a highly researched area but there are a few other studies that have provided Australian data:

- Pilgrim and Cordery (1975) Rainfall temporal patterns for design flood estimation. Proc. Amer. Soc. Civil Engrs., Jour. Hydraulics Div. 100(HY1):81-95.
- Srikanthan and Kennedy (1991) Rainfall antecedent to storm bursts from which temporal patterns were derived for "Australian Rainfall and Runoff"
- Minty and Meighen (1999) Rainfall antecedent to large and extreme rainfall bursts over southeast Australia
- Jordan et al. (2005) Growth curves and temporal patterns of short duration design storms for extreme events
- Scorah et al. (2015) Outcomes from a pilot study to investigate pre-burst rainfall depth for Australian Catchments.

Pilgrim and Cordery (1975) only has a limited discussion of measurements of antecedent rainfall prior to 20 min and 24 hour storms in Sydney and will not be reviewed in detail. The other studies are discussed below.

B.1 Srikanthan and Kennedy

Srikanthan and Kennedy (1991) used the storm data collated for the 1987 version of Australian Rainfall and Runoff to define pre-burst at two locations: Melbourne and Brisbane.

Pluviograph records of storms were available that contained the bursts used in the 1987 IFD analysis. Similar to other approaches, an algorithm was required to identify complete storm events. Moving backward in time from the start of a burst, the start of the storm was found when the proportion of rainfall in the next time interval was less than 0.5% of the resulting pattern.

Srikanthan and Kennedy (1991) provide pre-burst rainfalls for bursts of durations from 15 min to 24 hour and antecedent periods from 15 min to 24 hours. The distribution of pre-burst are specified as percentiles: 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 95 (Figure B1).

Points to note:

- Consistent with other studies, the pre-burst depth tends to decrease as storm duration increases.
- Pre-burst is not treated as a function of AEP, unlike the ARR2019 pre-burst.
- Pre-burst is available for a nominated antecedent period rather than representing all the rainfall in a storm that occurred prior to a burst. This approach is not used in other studies.
- Only a limited range of burst durations were considered (15 min, 30 min, 1 h, 6 h, 24 h).
- Only two locations were investigated: Brisbane and Melbourne.
- The distribution of pre-burst rainfall is available as a series of percentiles.
- Only pre-burst depths are provided, not pre-burst ratios, although these could be calculated, based on the 1987 IFD data.

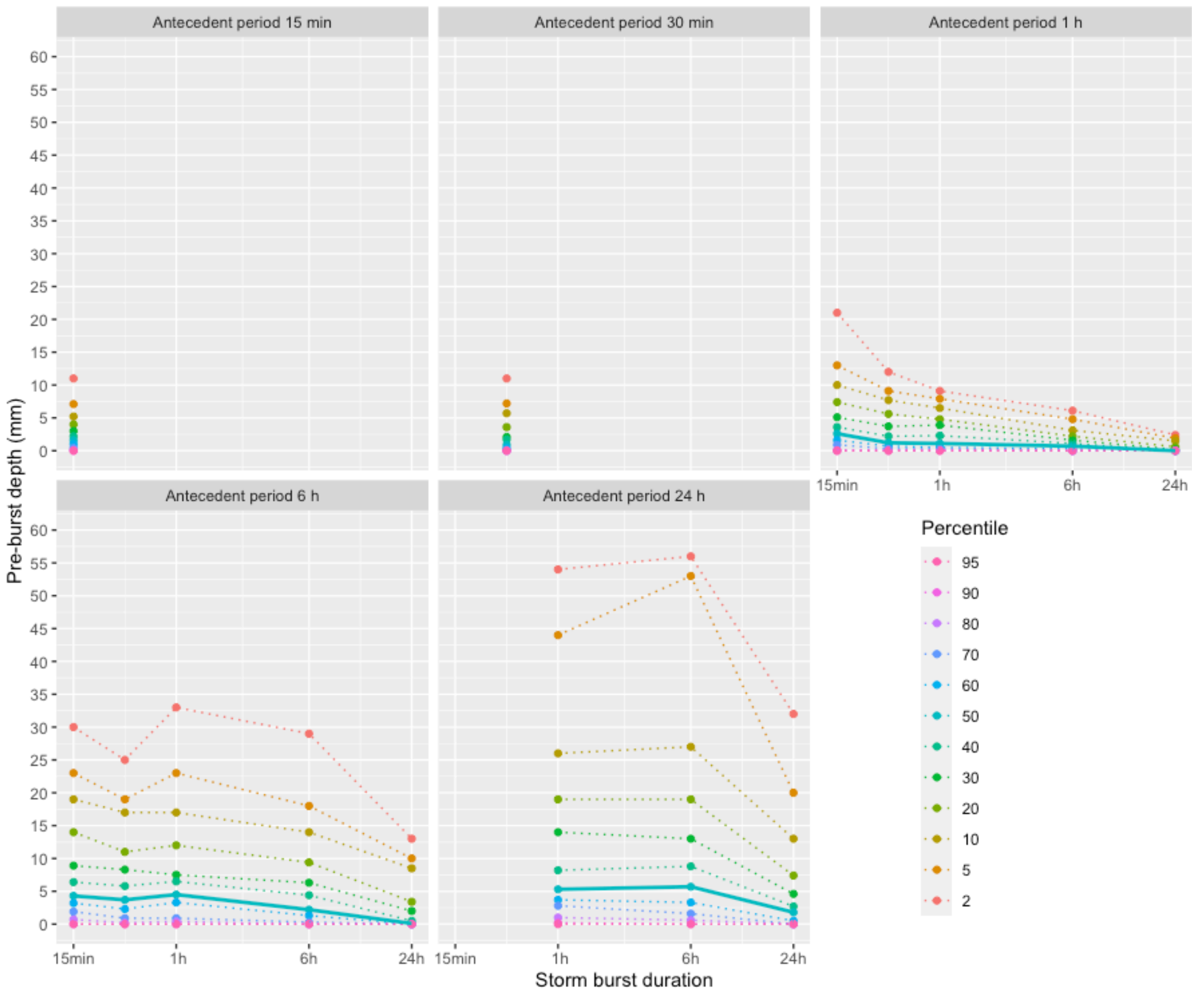


Figure B1: Pre-burst depths for Melbourne (Srikanthan and Kennedy, 1991)

B.2 Minty and Meighan

Minty and Meighan (1999) investigated rainfall antecedent to large and extreme bursts over south east Australia. This work used storm data collected for the development of the Generalised Southeast Australia Method (GSAM) for estimating probable maximum precipitation. The project is referred to as GSAMARP - Generalised Southeast Australia Method Antecedent Rainfall Project (Figure B2).

Pre-burst is presented as a percentage of burst depths for burst durations; 12, 24, 36, 48, 72, 96, 120 hours. There are also standard pre-burst periods for each burst duration (Table B1; Figure B3).

Minty and Meighan (1999) also provided temporal patterns for pre-burst rainfall; examples for the 12 hour burst are shown in Figure B4 for coastal and Figure B5 for inland.

Points to note:

- Temporal patterns are provided for pre-burst rainfalls. These temporal patterns are used in RORB.
- Pre-burst information is provided as a proportion of the burst depth rather than an absolute value. This means that pre-burst depth will vary with burst AEP unlike the values from Srikanthan and Kennedy (1991).
- The pre-burst details are mainly suited to rare events given they are derived from severe storms.

- Pre-burst details are only provided for bursts of 12 hours or longer.

Table B1: Standard length pre-burst periods (hours) for each burst duration

	Pre-burst period (hours)	
Burst duration (hours)	**Coastal**	**Inland**
12	39	24
24	33	21
36	27	18
48	21	15
72	15	6
96	9	0
120	3	0

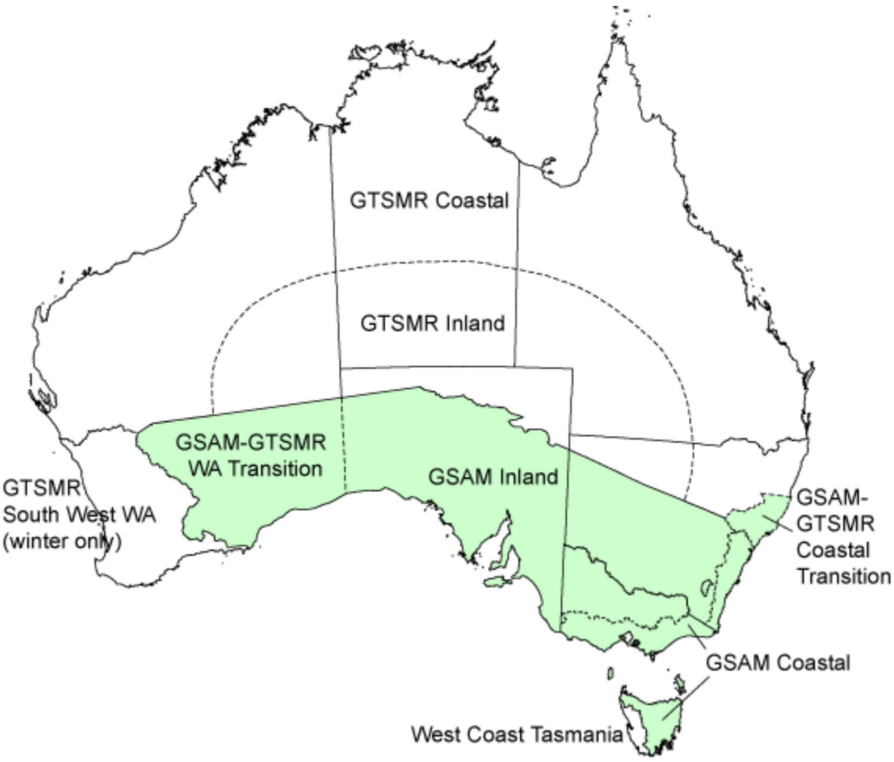


Figure B2: Area where the Generalised South East Australia Method (GSAM) is applied (Minty et al., 1996)

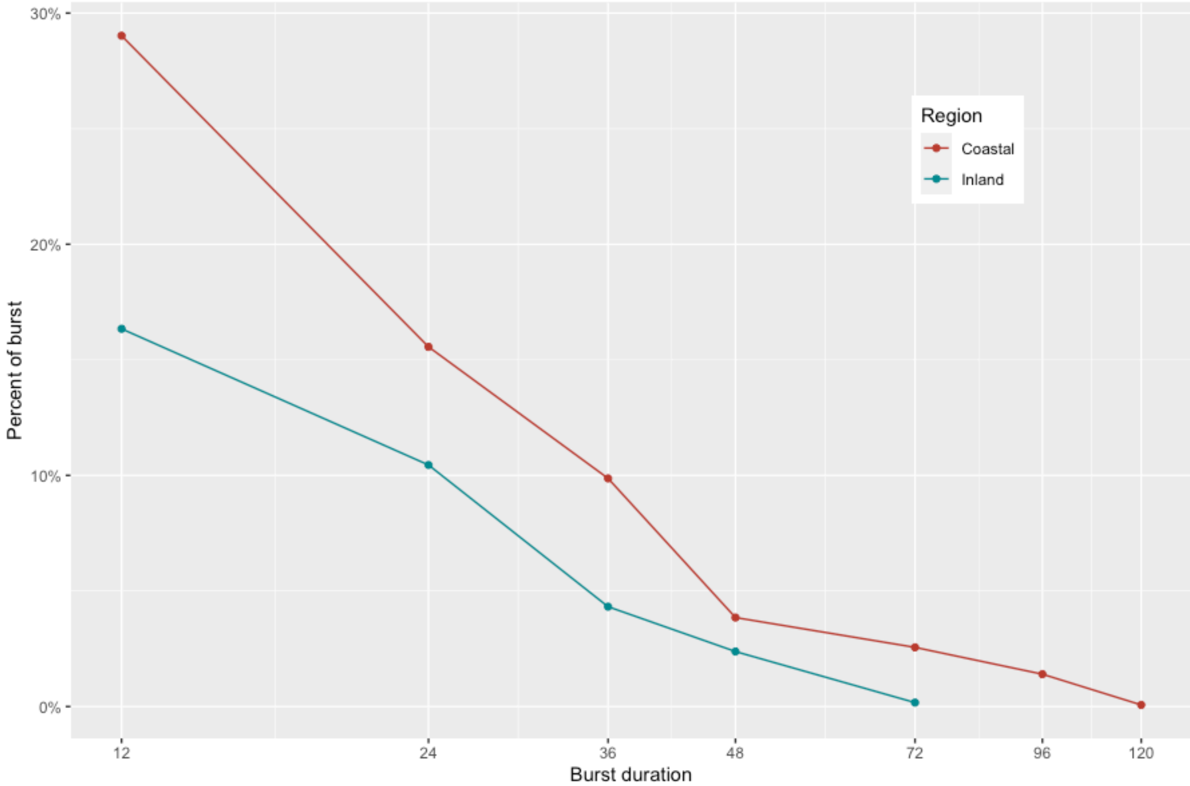


Figure B3: Pre-burst values as a percentage of burst depth (Minty and Meighan, 1999)

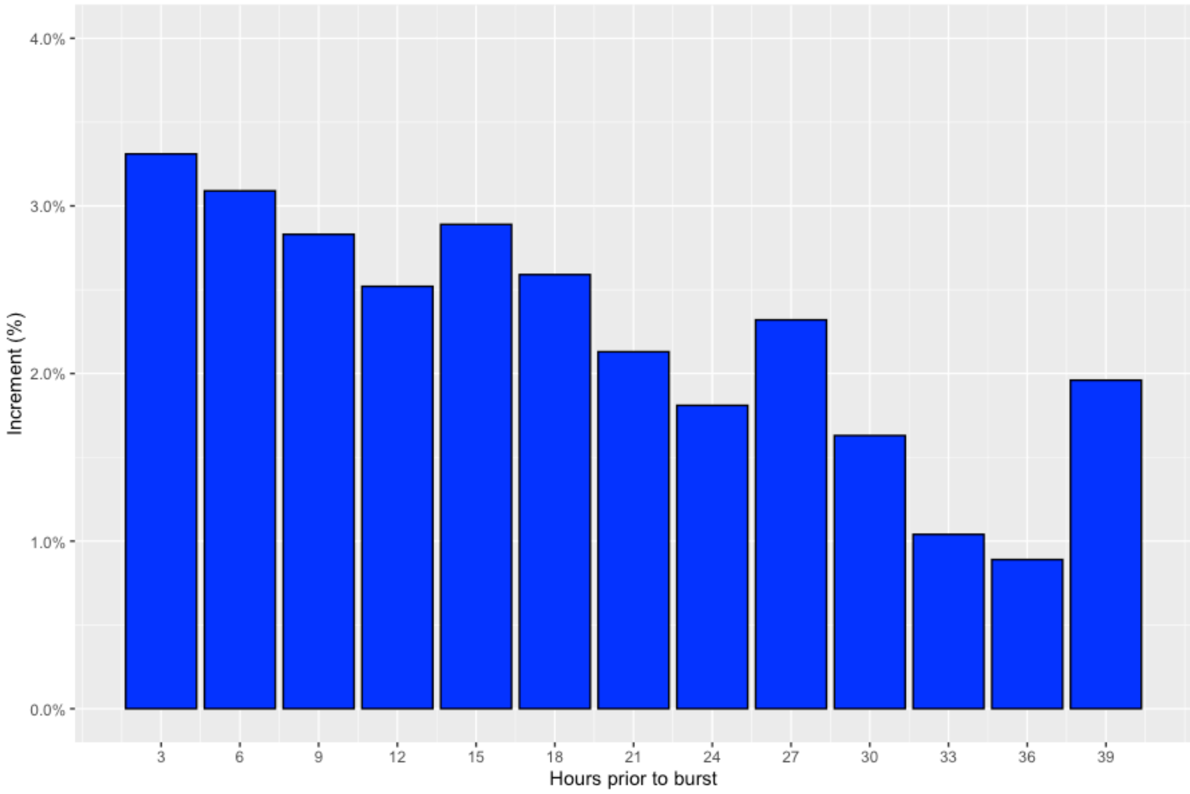


Figure B4: Pre-burst pattern for a 12 hour burst for GSAM coastal

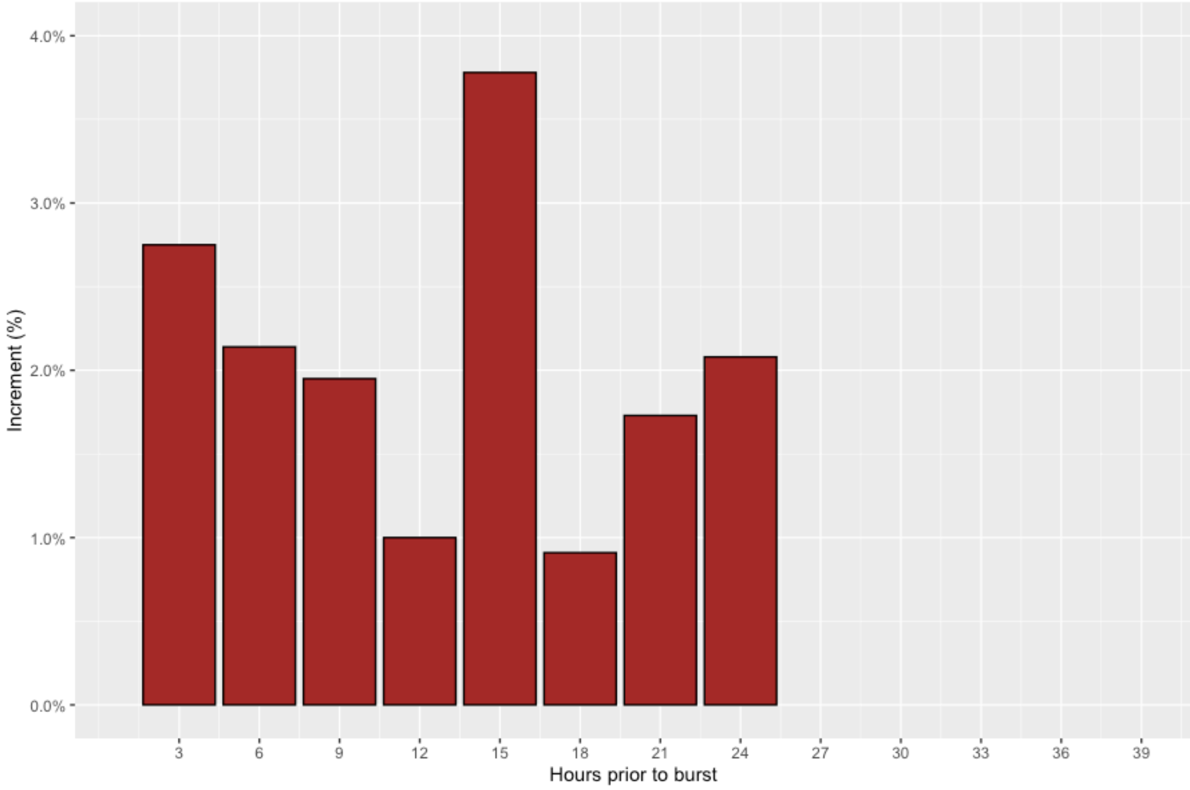


Figure B5: Pre-burst pattern for a 12 hour burst for GSAM inland

B.3 Jordan et al.

Jordan et al. (2005) analysed pre-burst information for ten short duration (12 hours or shorter) extreme storms. Pre-burst was generally small, averaging 3.2% of burst totals in the 7 hours prior to the extreme burst. Of the ten storms, 3 had no pre-burst rainfall, 4 had pre-burst rainfall of 1.3% to 3.5% of the burst and 3 recorded pre-burst rainfall that was 7.8% to 9.3% of the burst. A single pre-burst temporal pattern is provided based on analysis of these ten storms (Figure B6).

Points to note:

- Pre-burst information provided in Jordan et al. (2005) is only suitable for extreme events that exceed 1% AEP
- The pre-burst quantity of 3.5% of a 12 hour burst depth is much smaller than the 12 hour value provided by Minty and Meighan (1999) (see Figure B3).
- No information is provided on the distribution of pre-burst totals, for example, there is no information on percentiles as is provided by the data hub or Srikanthan and Kennedy (1991).

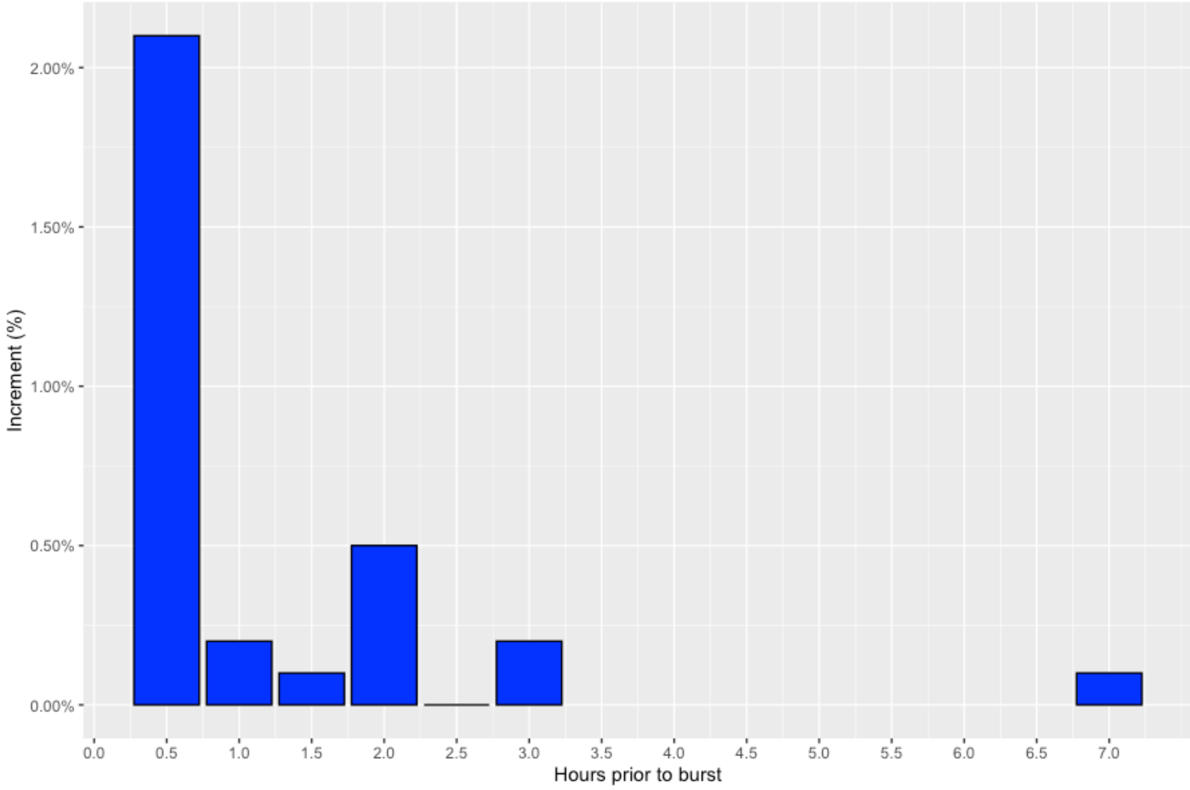


Figure B6: Pre-burst temporal pattern suitable for short duration extreme events.

B.4 Scorah et al.

The research on pre-burst undertaken by Scorah et al. (2015) is important because it provides a link to the work that was done to derive losses for Australian Rainfall and Runoff (ARRProject 6, Hill et al., 2014; 2015).

As part of the analysis of rainfall for the losses project, bursts were identified in the rainfall record for a range of durations (3, 6, 12, 24, 48 and 72 hours). Complete storms surrounding these bursts were defined using the following criteria:

- Set the start time based on a period of 12 hours with no significant rainfall
- Set the end time such that the surface runoff had effectively ended (had reduced to a few percent of the peak value)
- Move start and end times to 9 am to allow the use of daily rainfall data.

Pre-burst values were calculated based on these complete storms.

The information from Scorah et al., (2015) was made available for this review and was updated to use the 2016 IFD data to determine burst frequency.

B.5 Comparison

It is challenging to compare the various sources of pre-burst information. The data and the methods are inconsistent and different types of pre-burst information are provided. The differences are summarised in Table B2.

In summary:

- Values are provided as depths (mm), ratios, or both.
- Different burst durations are used.

- The geographical extent varies. Srikanthan and Kennedy (1991) provide data for a single location in Victoria, other methods cover the whole of Victoria.
- Pre-burst is sometimes provided as a function of AEP or may be constant with AEP. Some sources are only appropriate for rare events (rarer than 1 in 100) (Jordan et al., 2005; Minty and Meighen, 1999).
- Some sources provide a single pre-burst value, while others provide information on the distribution of pre-burst as percentiles, but when percentiles are provided, they vary between studies
- The pre-burst period is specified in some cases while in others, pre-burst is not provided as function of period.
- Two sources provide information on pre-burst temporal pattern.
- Burst frequency information is draw from different sources including the 1987 IFD data and the 2013 IFD data.

A comparison of pre-burst values is provided for Melbourne (Table B3). This is an attempt to compare like with like but with the following caveats.

- Values from Srikanthan and Kennedy are the median pre-burst based on a 24 hour pre-burst period. Information is only available for 1, 6 and 12 hour bursts.
- Data hub values are medians. Estimates are provided for two burst frequencies: 50% AEP and 1% AEP
- For Minty and Meighen (1999), pre-bursts are calculated from the ratios provided, multiplied by the burst depths for durations of 12 and 24 hours at Melbourne. Burst depths were obtained from 2016 IFD data. Only the 1% value is used here as the Minty and Meighen (1999) results are only appropriate for rare events.
- The Jordan et al. (2005) value is based on 3.2 % of the 1% burst depth. The recommendations in Jordan et al., (2005) are only appropriate for rare events.
- The Project 6 values are from Toomuc Creek, Pakenham. This is the closest Project 6 site to Melbourne but is 55 km to the southeast. The data used by Scorah et al. (2015) have been reworked using burst frequencies based on 2016 IFD data.

Table B2: Comparison of pre-burst sources

Source	Depths or ratios	Burst duration (hour)	Application to Victoria	AEP	Distribution of Pre-burst	Pre-burst period	Pre-burst temporal pattern	IFD
Srikanthan and Kennedy (1991)	Depths	1, 6, 24	Melbourne only	Constant with AEP	Percentiles: 2, 5, 10, 20, 30, 40, 50, 60 70, 80, 90, 95	15 min, 30 min, 1 h, 6 h, 25 h.	No	1987
Data hub	Depth and ratio	1, 1.5, 2, 3, 6, 12, 18, 24, 36, 48, 72	Whole of Victoria	6 AEP values: 50%, 20%, 10%, 5%, 2%, 1%	Percentiles: 10, 25, 50, 75, 90	Pre-burst depths and ratios are not provided as a function of period	No	2013
Minty and Meighen	Ratio	12, 24, 36, 72, 96, 120	Whole of Victoria with different values for inland and coastal GSAM areas	Constant with AEP	Single value	One period for each burst duration.	Yes	Based on extreme storms
Jordan et al., (2005)	Ratio	0.5 to 12	Whole of Victoria	Only suitable for extreme events (rarer than 1% AEP)	Single value	Single period, 7 hours	Yes	Based on extreme storms
Project 6 Hill et al., 2014; Scorah et al. 2015	Depth and ratio	3, 6, 12, 24, 48, 72	5 catchments: • Aire Ck • Axe Ck • McMahons • Tarago • Toomuc	Constant with AEP	Single median value (raw data also available)	Pre-burst depths and ratios are not provided as a function of period	No	2013 (updated to 2016)

Table B3: Comparison of pre-burst estimates

	Burst duration (hour)			
Source	**1**	**6**	**12**	**24**
Srikanthan and Kennedy: median, 24 hour antecedent period	5.3	5.7		1.8
Data hub: median 50% AEP	1	1.2	0.3	0
Data hub: median 1% AEP	2	7.1	8.2	0.9
Minty and Meighen: 1% AEP			29.6	20.4
Jordan et al.:1%	1.6	2.6	3.3	4.2
Project 6, Toomuc Creek: Median		9.4	3.0	3.0

Figure B8 also provides a comparison of the various methods. Points to note:

- The difference between Minty and Meighen (1999) and Jordan et al. (2005) for 12 and 24 hour bursts is surprising given both are based on historical information from extreme storms.
- Estimates provided by Minty and Meighen (1999) and Jordan et al. (2005) differ from the other values and may not be suitable for use where events are more common than "extreme".
- The data hub 50th percentile values, medianProject 6 values and 50th percentile Srikanthan and Kennedy values are all similar. The notches on the boxplots give an indication of the 95th percentile confidence limits for the median of theProject 6 data..
- The upper hinges of theProject 6 boxplots represent the 75th percentile. These are all contained within the 90th percentile values for Srikanthan and Kennedy (1991) and the data hub. Suggesting reasonable agreement.
- The 90th percentile values from Srikanthan and Kennedy (1991) are smaller than the 90th percentile data hub values. This is likely because the graph shows the data hub values based on the 1% AEP burst frequency. The next figure shows the effect of AEP.

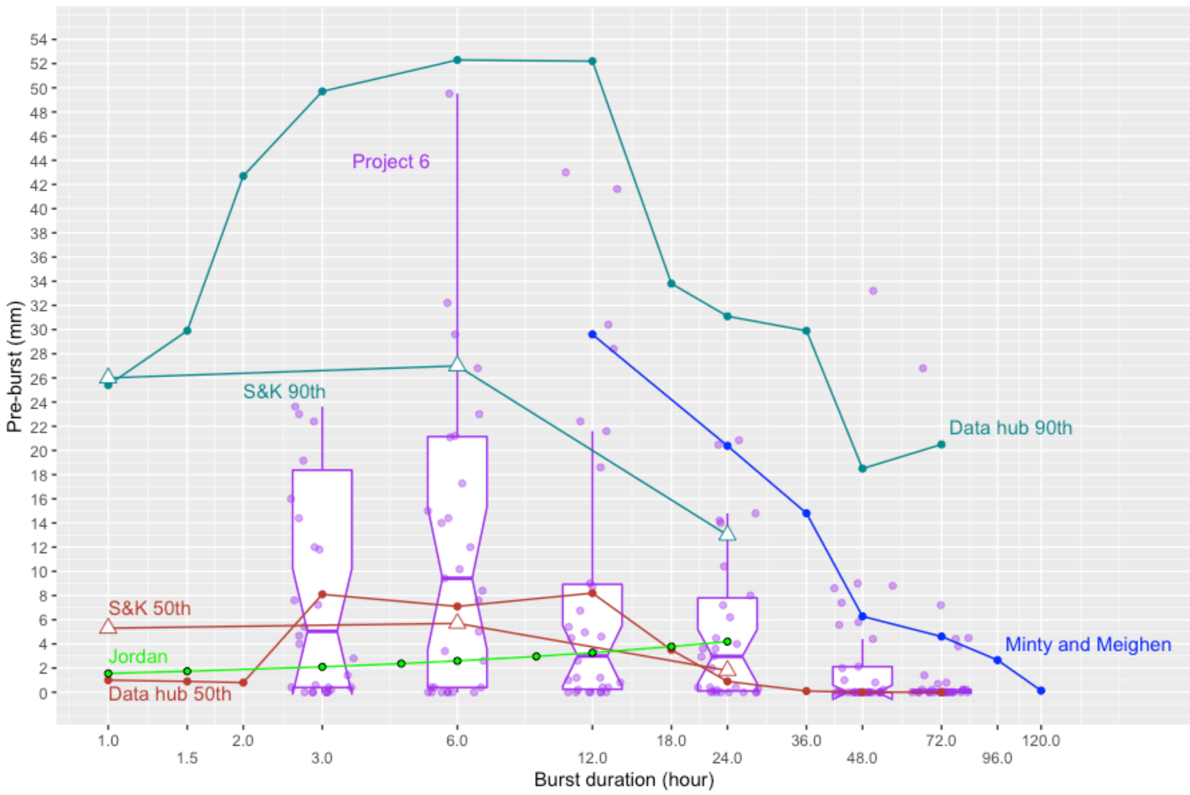


Figure B8: Comparison of pre-burst data; S&K refers to Srikanthan and Kennedy (1991). For data hub and Srikanthan and Kennedy (1991) two percentiles are show, 50th (median) and 90th. For data hub, Jordan and Minty and Meighen, values are based on the 1% AEP burst frequency. Project 6 data is for Toomuc Creek at Pakenham. Data are shown as boxplots and as raw values (purple circles). Outlying points extend beyond the tope of the graph.

Figure B9 shows a comparison between the methods taking account of AEP.

- The values from Project 6 and Srikanthan and Kennedy (1991) do not vary with AEP so are the same on each panel.
- The values for Minty and Meighen (1991) and Jordan et al. (2005) are based on extreme events so are only plotted on the 1% panel. As noted above, they may only be suitable for events rarer than 1%.
- For more common events, 5% AEP to 50% AEP, all methods provide similar results, both in terms of median and percentiles.
- The full range of Project 6 data is shown in these figures. The raw data has substantial scatter but the empirical 75th percentile estimates are all with in the 90th percentile values from the data hub and Srikanthan and Kennedy (1991). This suggests reasonable agreement.

Overall, this suggests that the data hub, Project 6 and Srikanthan and Kennedy (1991) provide similar pre-burst estimates for Melbourne for AEPs from 5% to 50%. The Project 6 and data hub pre-bursts are similar for the full range of AEPs and durations for this location.

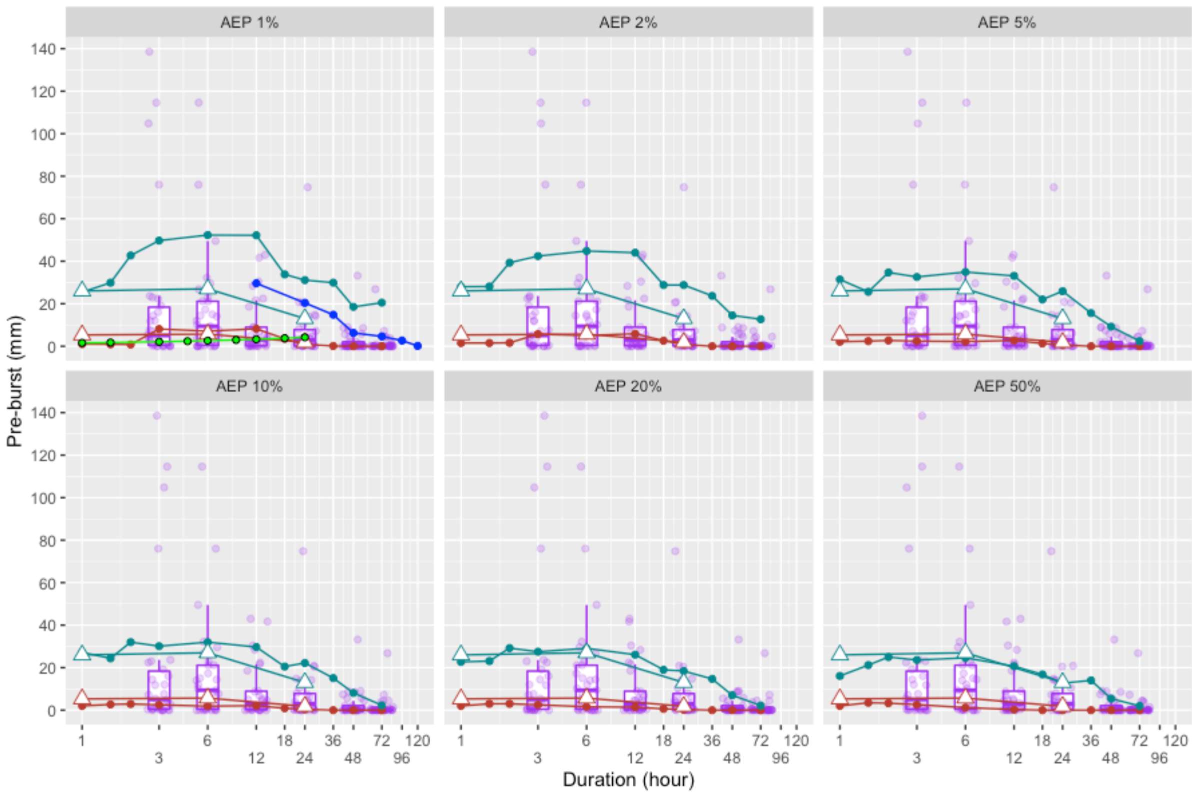


Figure B9: Pre-burst data for Melbourne for a range of AEPs and methods. See previous figure for a legend

Appendix C: Pre-burst data for a transect across Victoria

This appendix includes maps and figures that show information for a transect across Victoria:

- Pre-burst depth (Figures C1 and C2)
- Pre-burst ration (Figures C3 and C4)
- Continuing loss (Figures C5 and C8)
- Storm initial loss (Figures C6, C8 and C9)
- Burst initial loss (Figures C7 and C9)

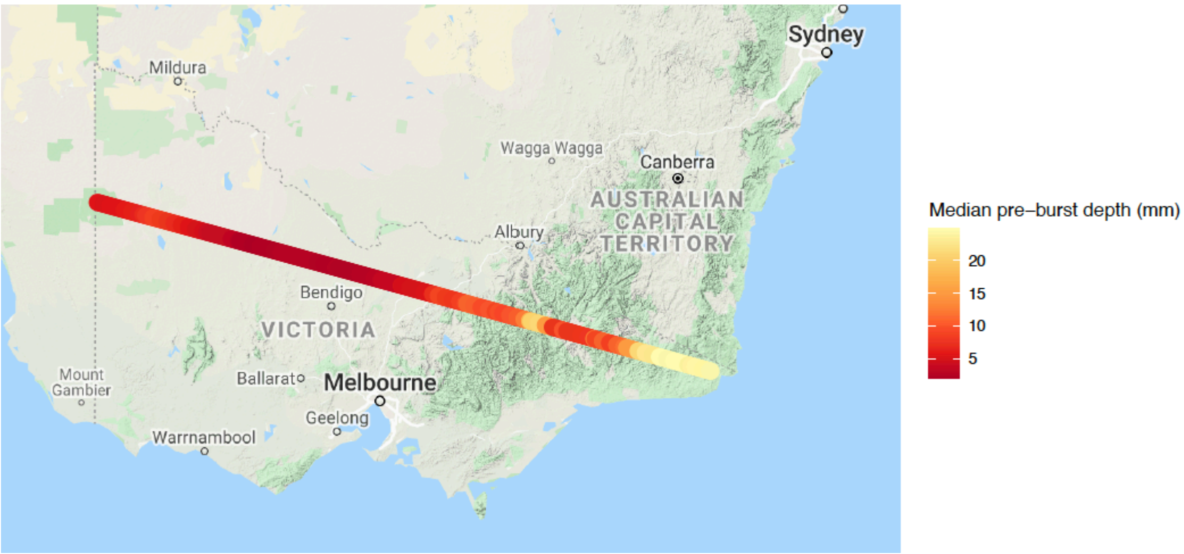


Figure C1: Map - median pre-burst depth (1% AEP, 12 hour duration)

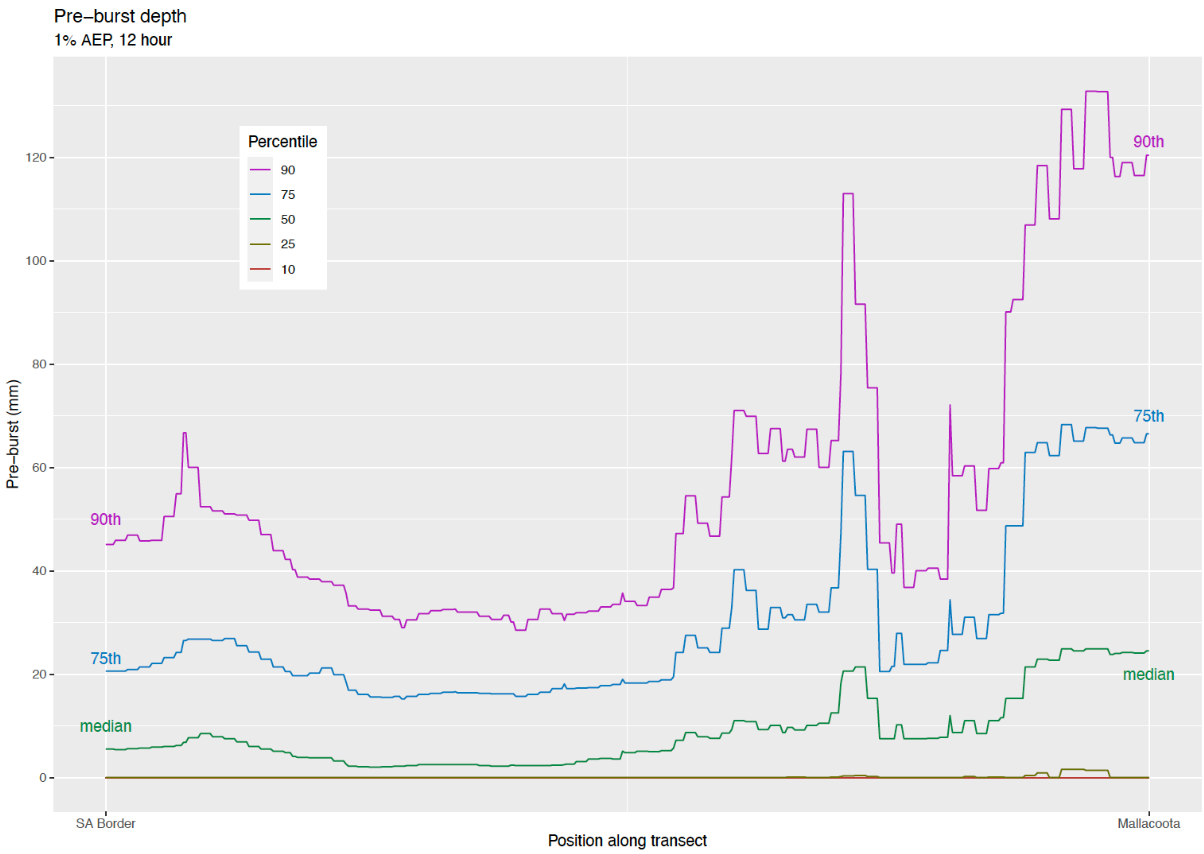


Figure C2: Pre-burst depth (1% AEP, 12 hour duration)

Figure C3: Map - median pre-burst ratio (1% AEP, 12 hour duration)

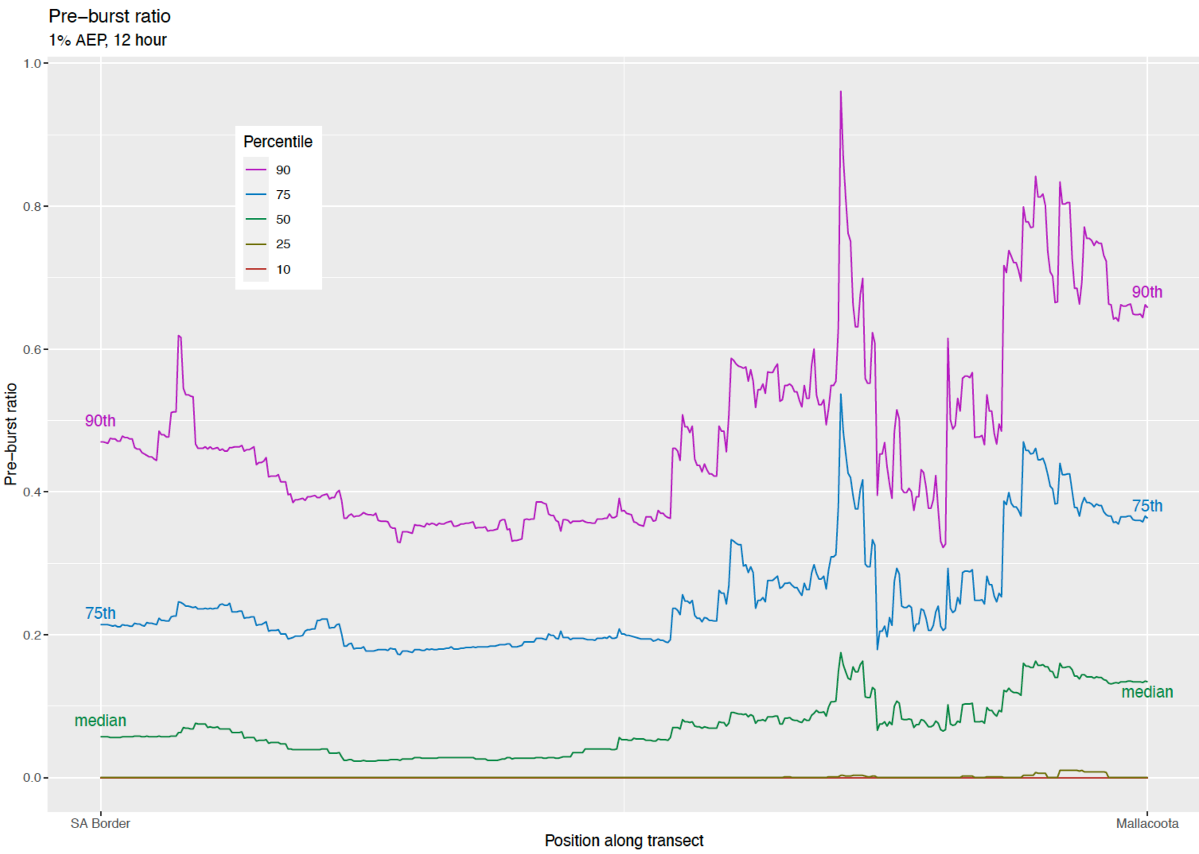


Figure C4: Pre-burst ratio (1% AEP, 12 hour duration)

Figure C5: Map - Continuing loss

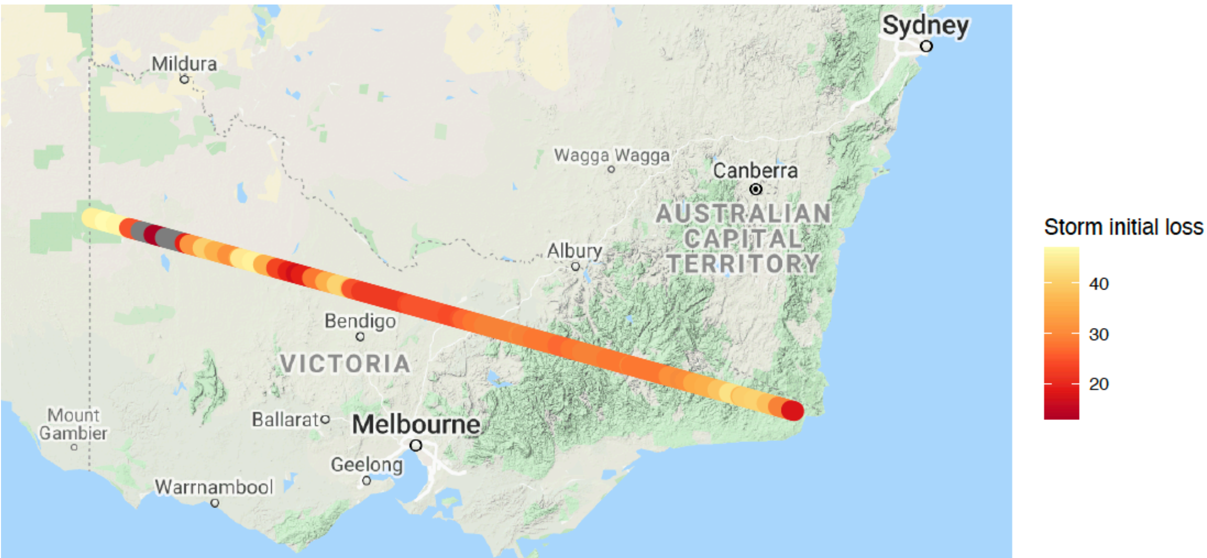


Figure C6: Map – Initial loss

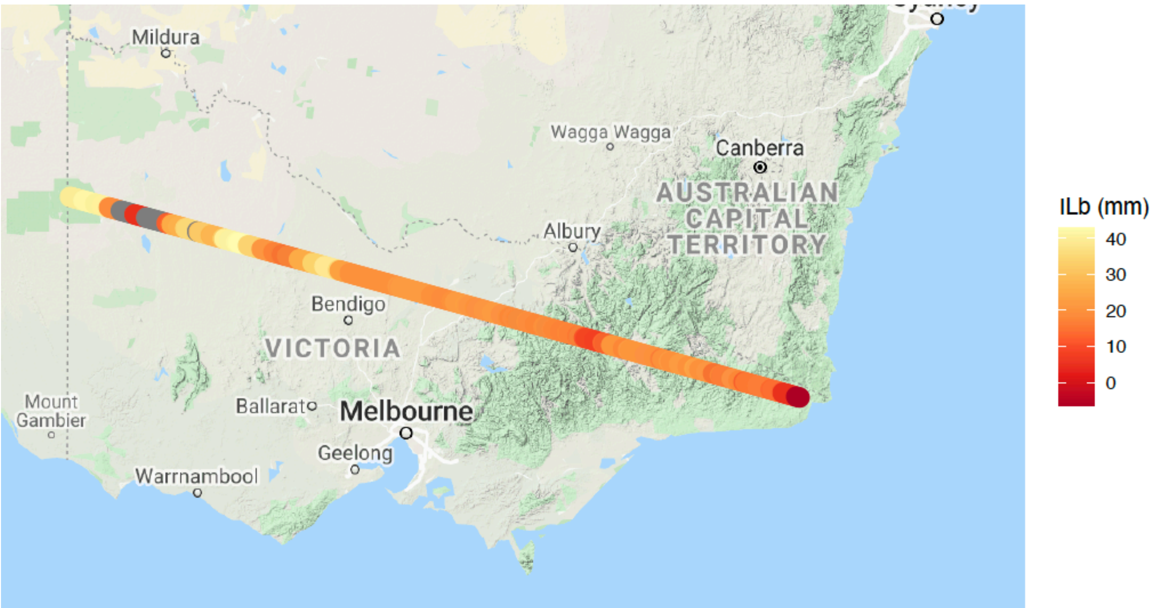


Figure C7: Map – burst initial loss

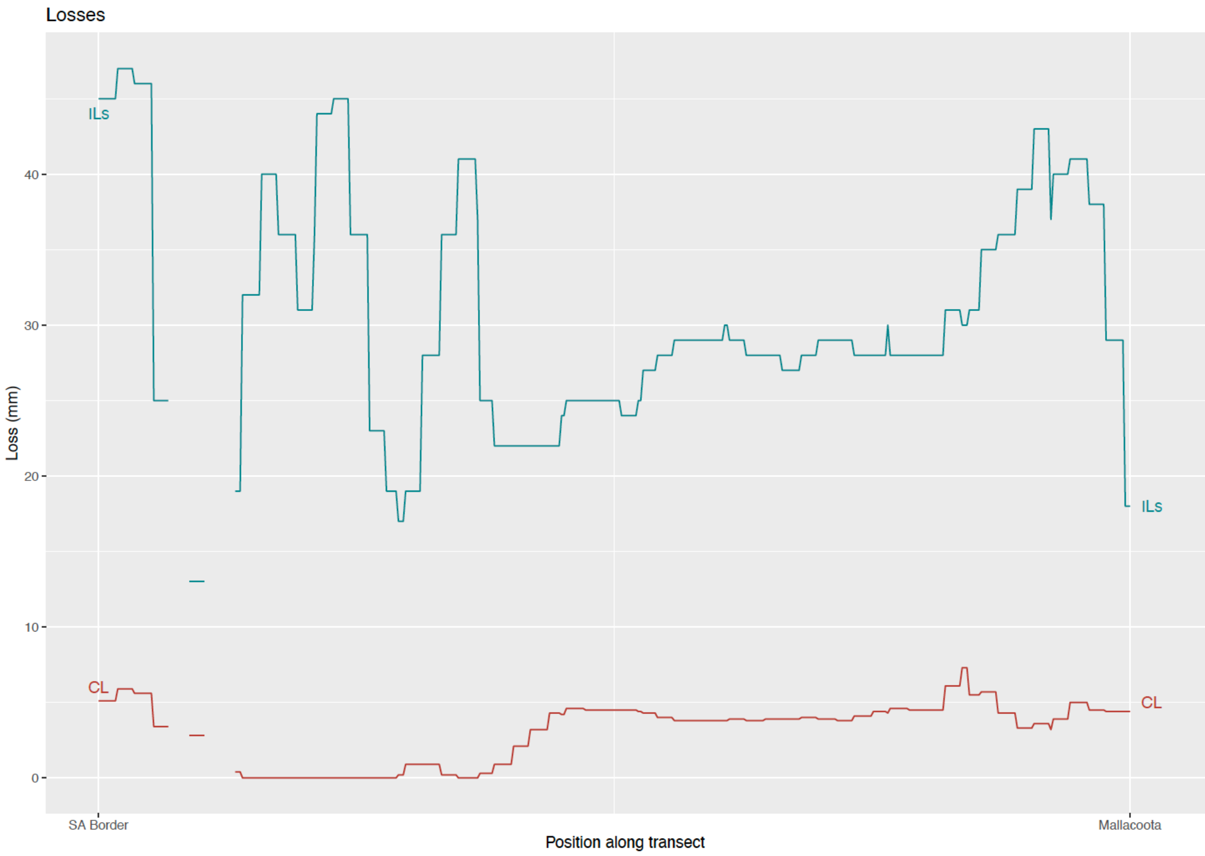


Figure C8: Continuing loss and median storm initial loss

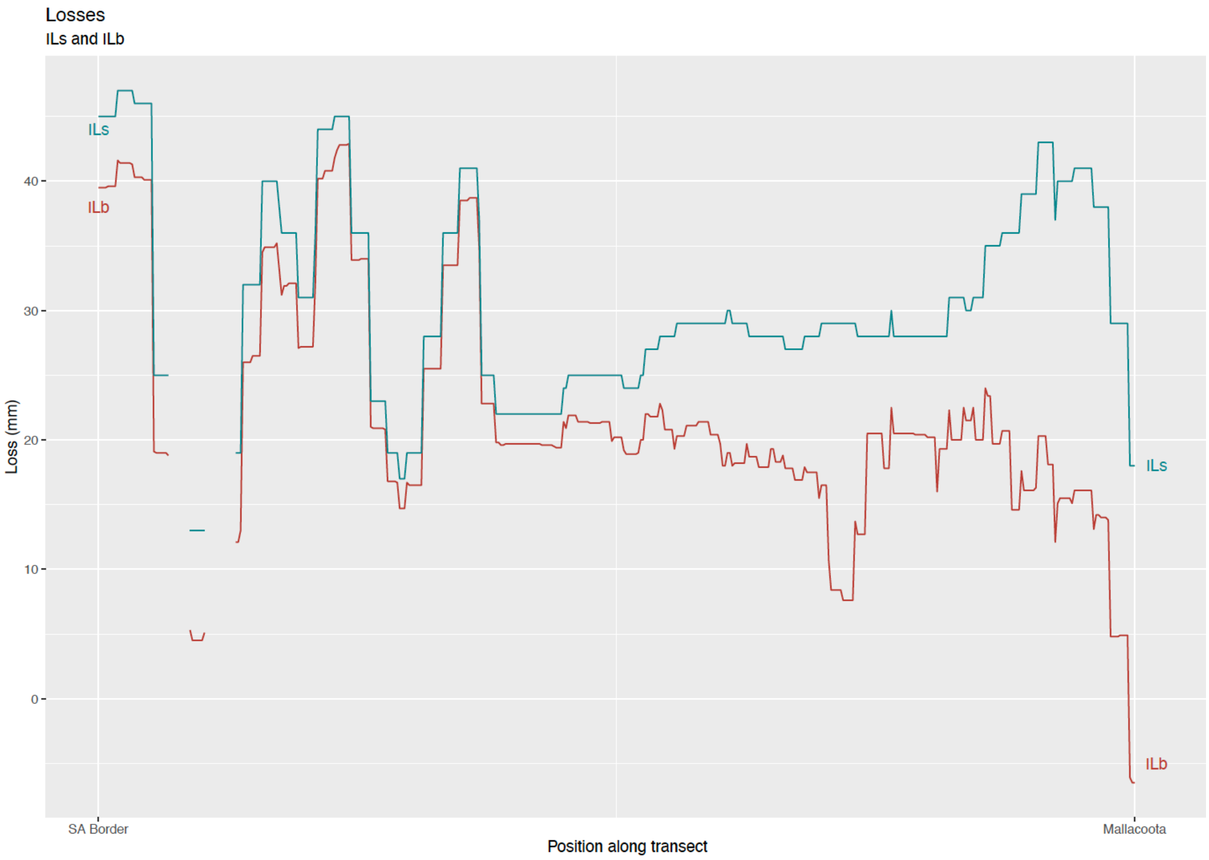


Figure C9: Storm initial loss (ILs) and burst initial loss (ILb)

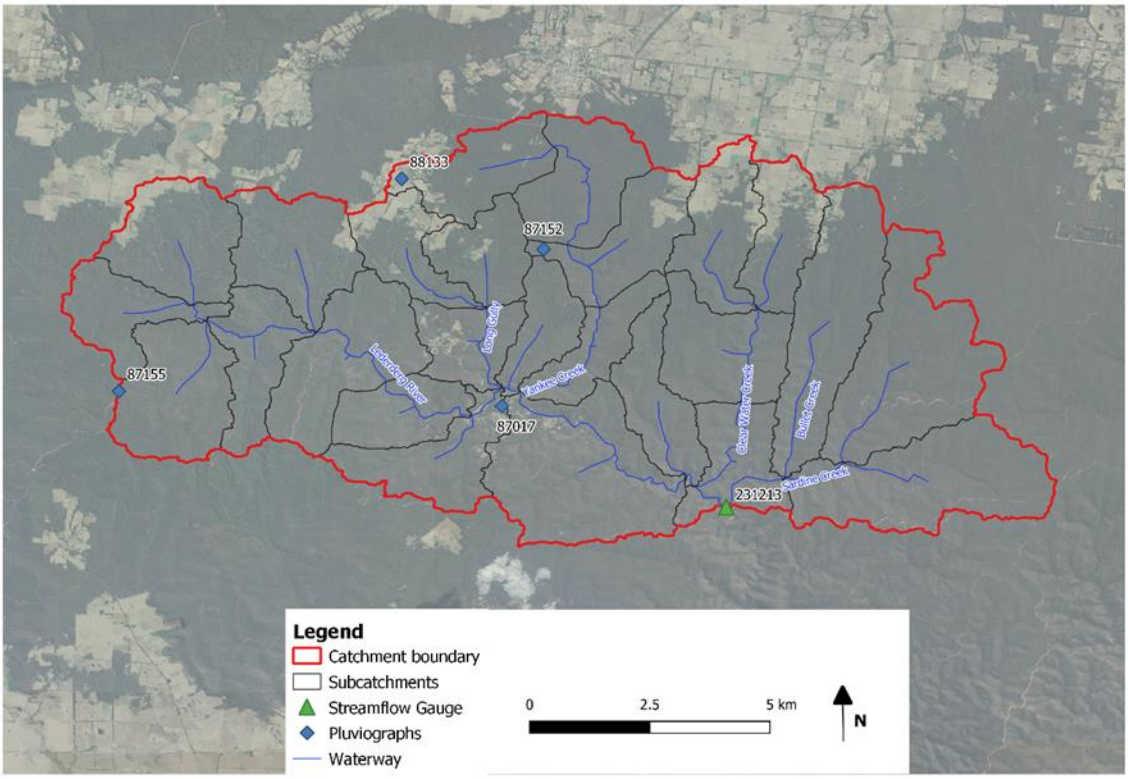
Appendix B RORB Model Calibration

B.1 Lerderderg River at Sardine Creek Obrien Crossing

B.1.1 Model Development

As noted previously, a new RORB model was developed and calibrated for this catchment. The RORB model was created by sub-dividing the catchment into a series of subareas to suit the catchment topography and other features such as the location of gauging station. The RORB model development was based on the hydrologically enforced one second resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). The DEMs were derived from the SRTM data acquired by NASA in February 2000 (Gallant et al., 2011) and were publicly released under Creative Commons licensing from November 2011.

Four different types of reaches are recognised in RORB, having different properties and different relative delay times and identified as 1 for natural, 2 for excavated but unlined, 3 for lined channel or pipe and 4 for drowned reach. Natural reaches were used for all areas based on aerial imagery of the catchment. The RORB model sub-areas and locations of key gauges can be seen in Figure B-1.



- **Figure B-1: Catchment boundary and rainfall and streamflow gauge locations**

B.1.2 Calibration

RORB models are based on catchment geometry and topographic data, and the two principal routing parameters are k_c and m. The parameter m describes the degree of non-linearity of the catchment's response to rainfall excess, while the parameter k_c describes the delay in the catchment's response to rainfall excess. A value of 0.8 was adopted for the non-linearity parameter, m, for this study, which is recommended by Laurenson et al. (2010) and recommended in Book 8 of Australian Rainfall and Runoff (Nathan and Weinmann, 2016). The routing parameter, k_c, is selected by calibrating the RORB model to historic floods. The selection of k_c is discussed below.

RORB only models the surface runoff and therefore for each calibration event the baseflow component was removed from the recorded total streamflow hydrograph by manually estimating the baseflow component using the same techniques outlined in Section 5.7. For each of the events, baseflow was a small proportion of the total flow.

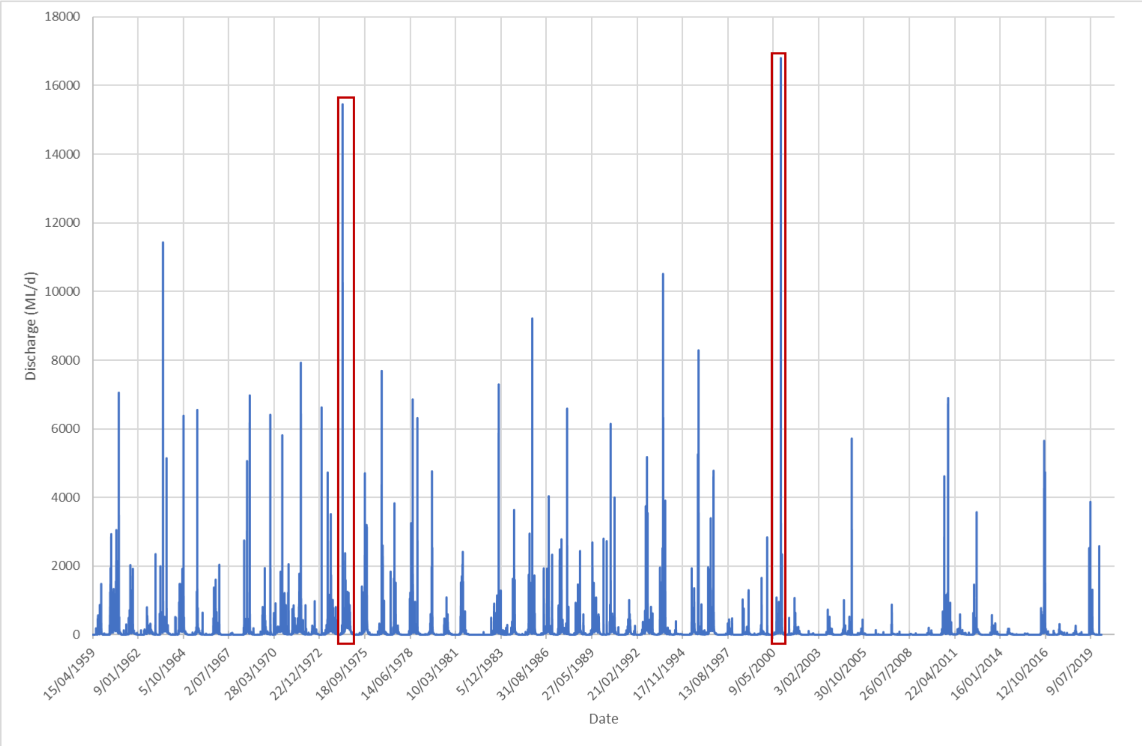
The remaining RORB model parameters represent rainfall losses, using either an initial loss/continuing loss model, or an initial loss/proportional loss (i.e. runoff coefficient) model. An initial loss/continuing loss model was adopted for this study as discussed in Section 5.4.

In general, the calibration approach was:

- Adjustment of the k_c to achieve a fit to the shape of the recorded hydrograph. The model was run interactively with various trial values of k_c, and the value giving best reproduction of the observed data was adopted.
- Initial loss directly affects the start of the hydrograph rise, but also affects the time distribution of rainfall excess and hence the hydrograph peak, especially for long storms with large variations of intensity. The continuing loss generally affects the hydrograph volume. The initial and continuing loss were adjusted in conjunction to attempt to match the start of the hydrograph rise and achieve a reasonable fit between the modelled and observed hydrograph volumes.

The two largest events have been chosen for the purposes of calibration. These events were chosen on the basis of peak flows at Lerderderg River at Sardine Creek Obrien Crossing (231213). Figure B-2 shows the flows recorded and calibration events selected at Lerderderg River at Sardine Creek Obrien Crossing (231213). The calibration events chosen were May 1974 and October 2000. Although, a flood study focused on a particular catchment would typically calibrate a rainfall-runoff model to more events, the 2 events were considered sufficient for the benchmarking study to confirm the routing parameters.

Calibration of the RORB model was undertaken by setting up historical storm files and running the RORB model with routing parameters and losses such that a match was achieved against the recorded flood hydrographs.



- **Figure B-2: Lerderderg River at Sardine Creek Obrien Crossing (231213) – events chosen are circled in red**

May 1974

For the May 1974 event, the closest pluviographs with available information were Newbury (88133), Lerderderg No4 Recorder (87152), Blackwood (87017), Lerderderg No4 Recorder (87155). The temporal pattern of rainfall in each subarea was defined using these pluviographs. Figure B-3 shows the pluviograph information available at each gauge.

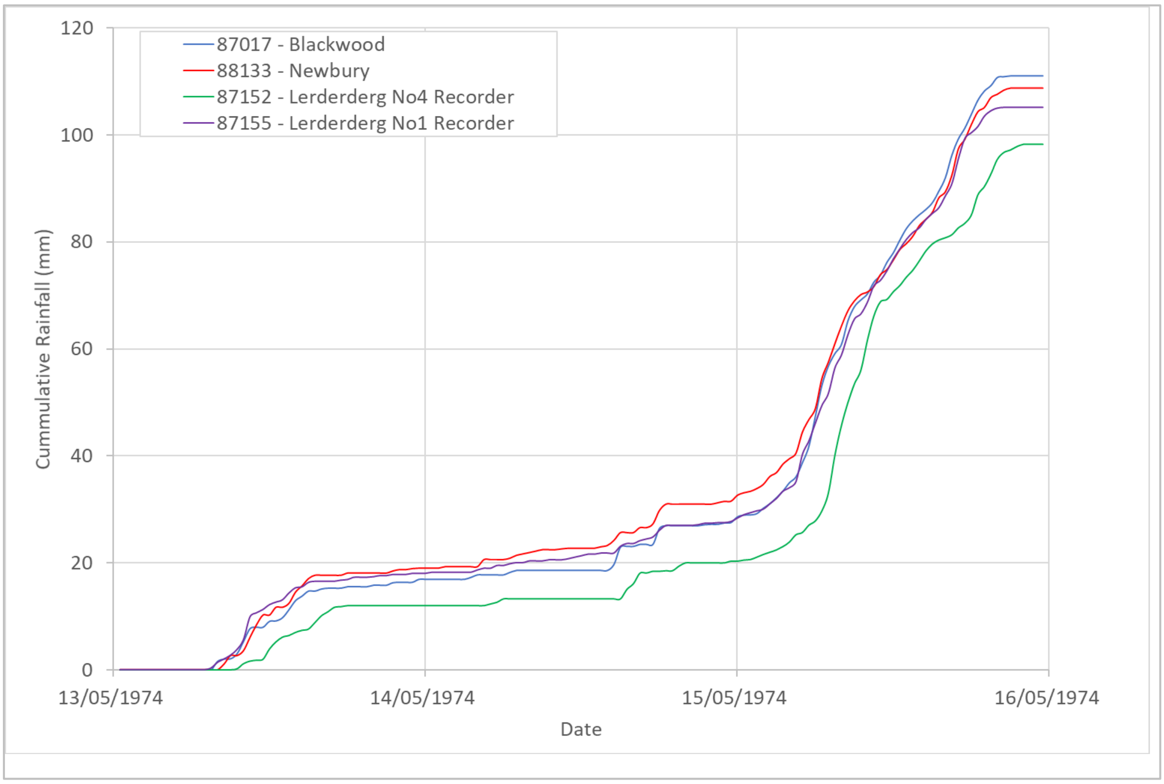


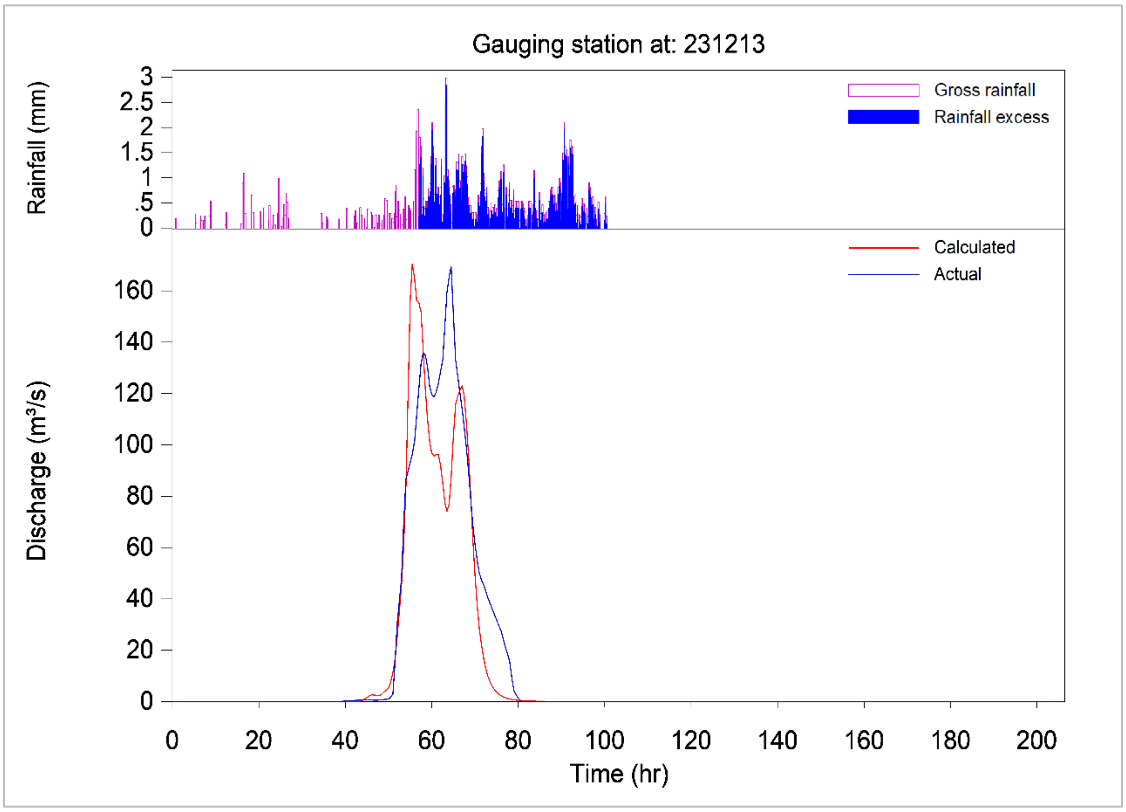
Figure B-3: Cumulative pluviograph records for May 1974 for the gauges Newbury (88133), Lerderderg No4 Recorder (87152), Blackwood (87017), Lerderderg No4 Recorder (87155)

Rainfall depths were estimated by interpolating the AWAP rainfall data to the RORB model subarea centroids. Figure B-3 shows the cumulative rainfall depths across the catchment. Although the overall depth applied to the catchment was determined from the AWAP record, the individual pluviograph records were checked against these values for consistency. Pluviographs were also used for the rainfall temporal patterns.

A summary of the calibration parameters for the May 1974 event are shown in Table B-1 with the hydrograph shown in Figure B-4. Overall, the calibration shows a reasonable match to the peak flow, timing and volume of the recorded May 1974 event. This event had a double peak which the calibration was unable to reproduce, however it was deemed acceptable as the peak flow and volumes matched the event.

Table B-1: Summary of calibration parameter values for May 1974

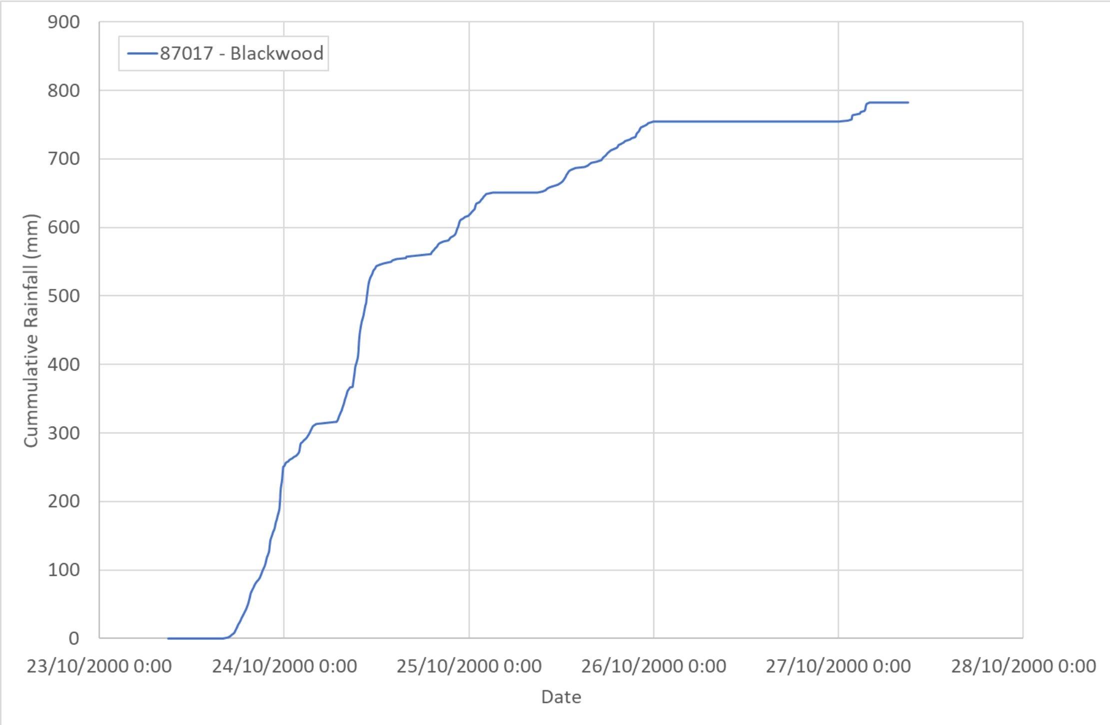
Gauge	Name	k_c	m	IL (mm)	CL (mm/h)
231213	Lerderderg River at Sardine Creek Obrien Crossing	13	0.8	20	1



- **Figure B-4: RORB calibration at Gauge 231213 May 1974 event**

October 2000

For the October 2000 event, the closest pluviograph with available information was Blackwood (87017). The temporal pattern of rainfall in each subarea was defined using this pluviograph. Figure B-5 shows the pluviograph information available at this gauge.



- **Figure B-5: Cumulative pluviograph record for October 2000 for gauge Blackwood (87017)**

Rainfall depths were estimated by interpolating the AWAP rainfall data to the RORB model subarea centroids. Figure B-5 shows the cumulative rainfall depths across the catchment. Although the overall depth applied to the catchment was determined from the AWAP record, the individual pluviograph records were checked against these values for consistency. Pluviographs were also used for the rainfall temporal patterns.

A summary of the calibration parameters for the October 2000 event are shown in Table B-2 with the hydrograph shown in Figure B-6. Overall, the calibration shows a reasonable match to the shape and volume of the recorded October 2000 event. To match the volume and timing as close as possible the peak flow was slightly underestimated.

- **Table B-2: Summary of calibration parameter values for October 2000**

Gauge	Name	k_c	m	IL (mm)	CL (mm/h)
231213	Lerderderg River at Sardine Creek Obrien Crossing	12	0.8	10	0.3

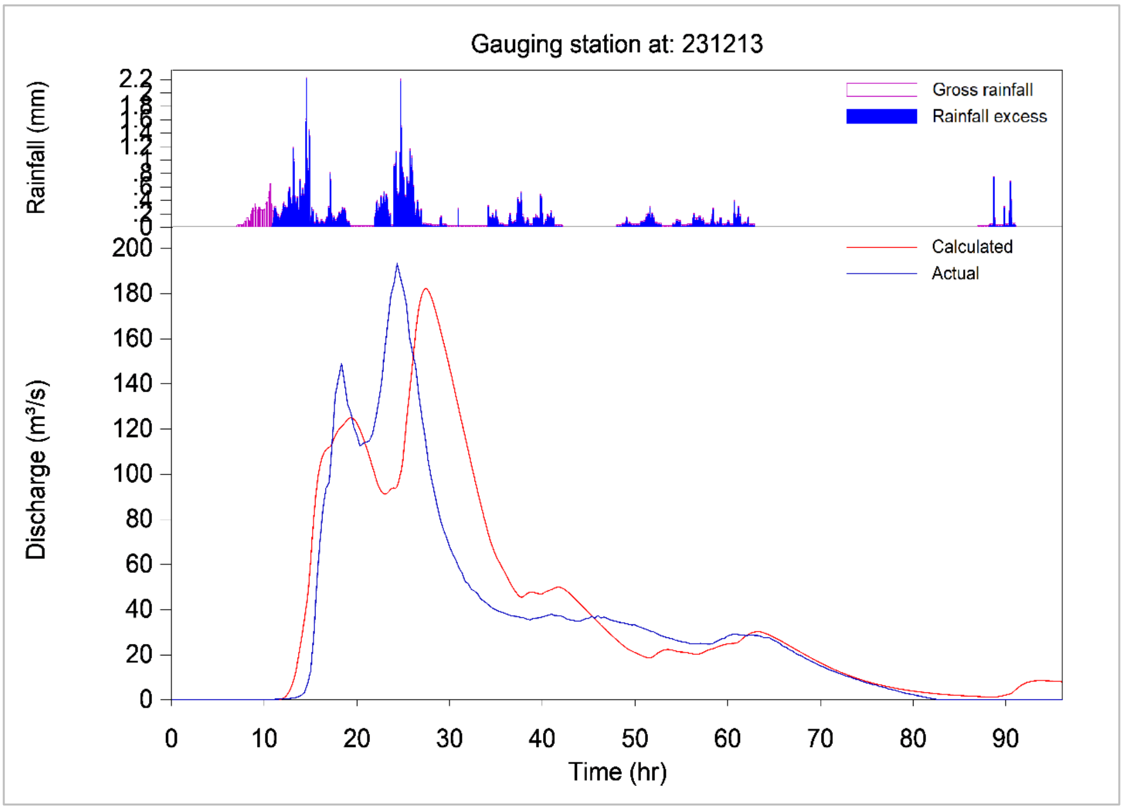


Figure B-6: RORB calibration at Gauge 231213 October 2000 event

B.1.3 Adopted RORB parameter values

In general, the calibration provided a reasonable fit for both events. As with all hydrological modelling the variation between the recorded and modelled hydrograph can be due to a number of things i.e. change in catchment conditions, data errors, baseflow separation error, rainfall variability, rating curve errors and the lack of adequate data to represent the variability across the catchment and the RORB model being only a representation of a variable and complex rainfall runoff process. Table B-3 summarises the k_c values adopted from the calibration process. A k_c value of 13 was adopted for design based on the quality of the calibration and the appropriateness of the d_{av}.

Table B-3: Summary of the calibrated k_c values

Gauge	Name	1974	2000	Adopted k_c	d_{av}*	k_c/d_{av}
231213	Lerderderg River at Sardine Creek Obrien Crossing	13	12	13	10.44	1.24

* d_{av} is the weighted average flow distance to the catchment outlet (this is calculated automatically in the RORB model)

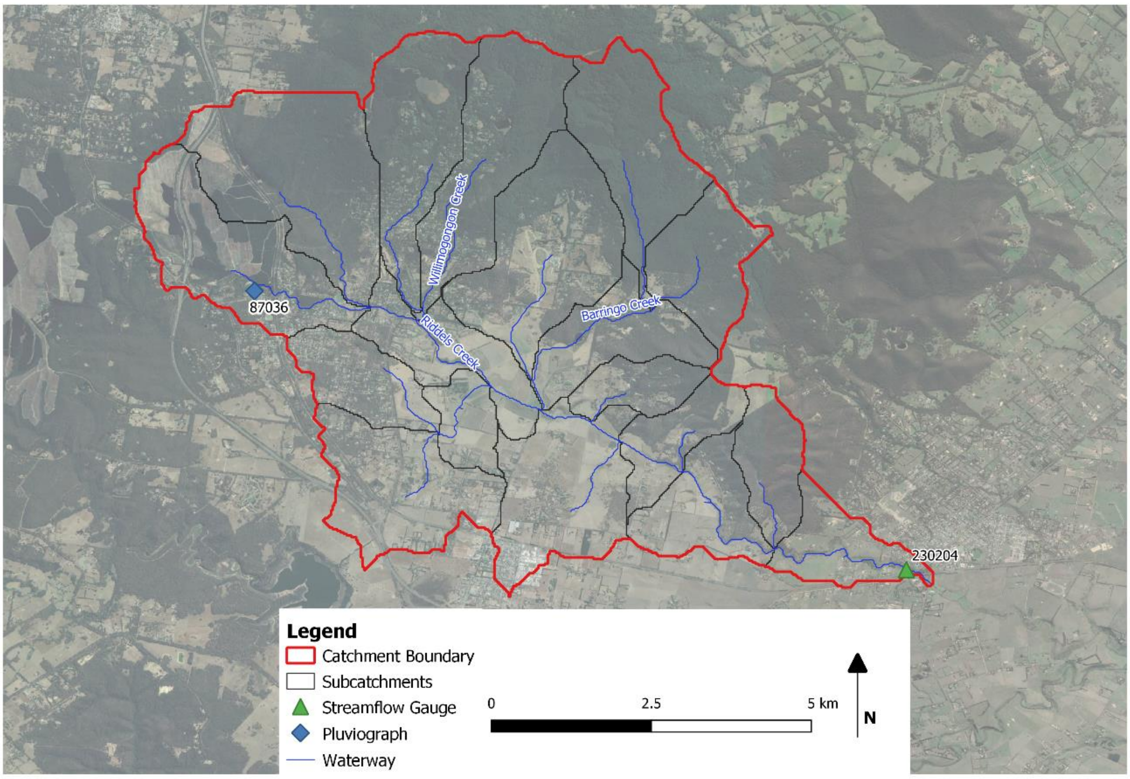
B.2 Riddles Creek

B.2.1 Model Development

As noted previously, a new RORB model was developed and calibrated for this catchment. The RORB was created by sub-dividing the catchment into a series of subareas to suit the catchment topography and other features such as the location of gauging station. The RORB model development was based on the hydrologically enforced one second resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). The DEMs were derived from the SRTM data acquired by NASA in February 2000 (Gallant et al., 2011) and were publicly released under Creative Commons licensing from November 2011.

Four different types of reaches are recognised in RORB, having different properties and different relative delay times and identified as 1 for natural, 2 for excavated but unlined, 3 for lined channel or pipe and 4 for drowned reach. Natural reaches were used for all areas based on aerial imagery of the catchment.

The hydrological catchments and location of key gauges can be seen in Figure B-7.



- **Figure B-7: Catchment boundary and rainfall and streamflow gauge locations**

B.2.2 Calibration

RORB models are based on catchment geometry and topographic data, and the two principal routing parameters are k_c and m. The parameter m describes the degree of non-linearity of the catchment's response to rainfall excess, while the parameter k_c describes the delay in the catchment's response to rainfall excess. A value of 0.8 was adopted for the non-linearity parameter, m, for this study, which is recommended by Laurenson et al. (2010) and recommended in Book 8 of Australian Rainfall and Runoff (Nathan and Weinmann, 2016). The routing parameter, k_c, is selected by calibrating the RORB model to historic floods. The selection of k_c is discussed below.

RORB only models the surface runoff and therefore for each calibration event the baseflow component was removed from the recorded total streamflow hydrograph by manually estimating the baseflow component using the same techniques outlined in Section 5.7. For each of the events, baseflow was a small proportion of the total flow.

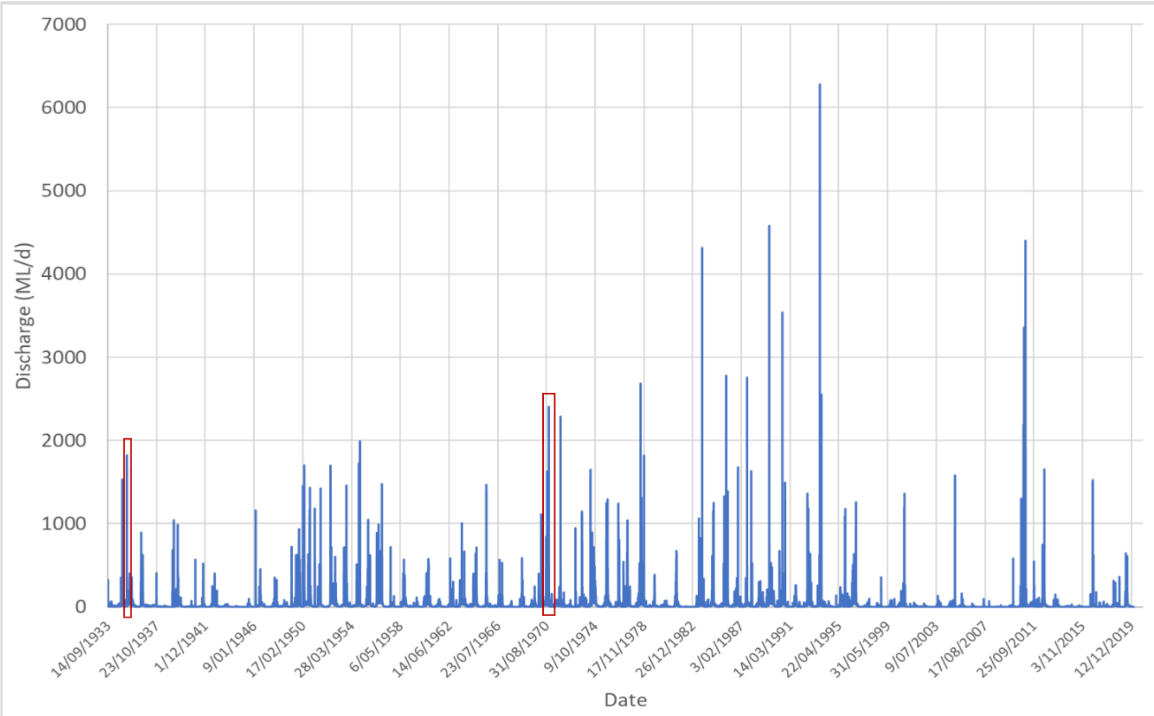
The remaining RORB model parameters represent rainfall losses, using either an initial loss/continuing loss model, or an initial loss/proportional loss (i.e. runoff coefficient) model. An initial loss/continuing loss model was adopted for this study as discussed in Section 5.4.

In general, the calibration approach was:

- Adjustment of the k_c to achieve a fit to the shape of the recorded hydrograph. The model was run interactively with various trial values of k_c, and the value giving best reproduction of the observed data was adopted.
- Initial loss directly affects the start of the hydrograph rise, but also affects the time distribution of rainfall excess and hence the hydrograph peak, especially for long storms with large variations of intensity. The continuing loss generally affects the hydrograph volume. The initial and continuing loss were adjusted in conjunction to attempt to match the start of the hydrograph rise and achieve a reasonable fit between the modelled and observed hydrograph volumes.

Two events have been chosen for the purposes of calibration. An analysis of the pluviography data indicated that many of the large flood events post 1978 had poor data resulting in major flood events not having data throughout the peak of the flood. As a result, smaller flood events which had better quality data to undertake the analysis was used. These events were chosen on the basis of peak flows at Riddells Creek at Riddells Creek (230204). Figure B-8 shows the flows recorded at Riddells Creek at Riddells Creek (230204). The calibration events chosen were April 1935 and November 1970.

Calibration of the RORB model was undertaken by setting up historical storm files and running the RORB model with routing parameters and losses such that a match was achieved against the recorded flood hydrographs.



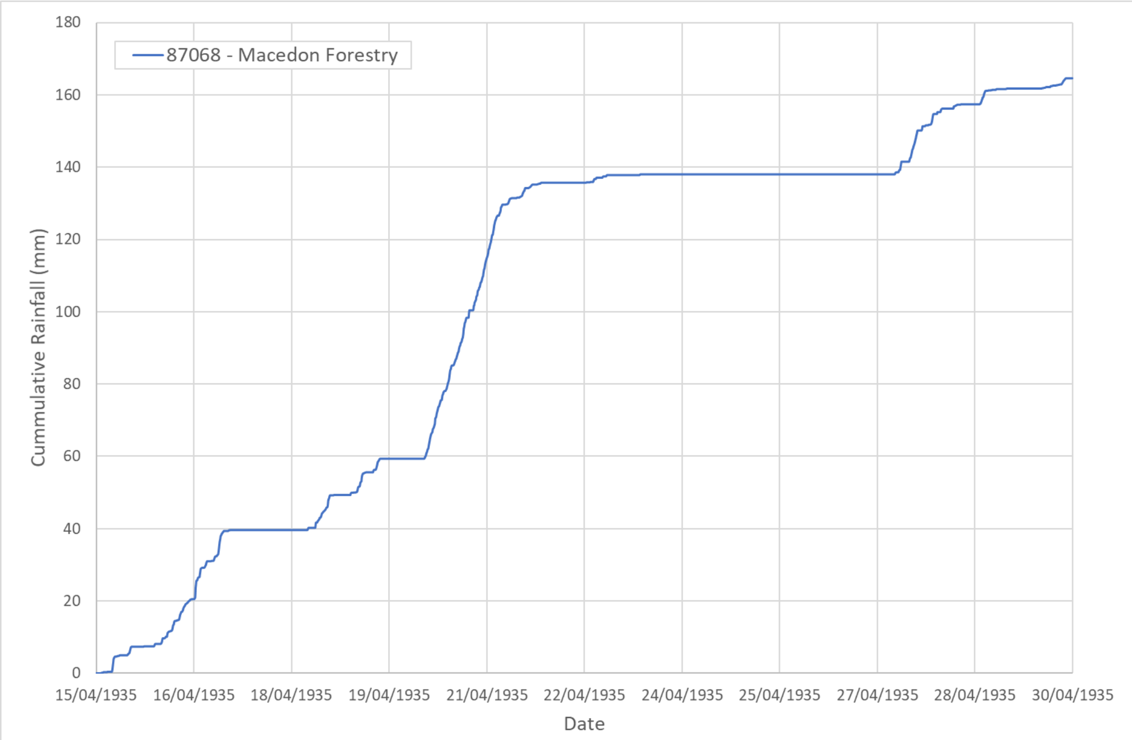
■ Figure B-8: Riddells Creek at Riddells Creek (230204)– events chosen are circled in red

April 1935

For the April 1935 event, the closest pluviograph with available information was Macedon Forestry (87036). The temporal pattern of rainfall in each subarea was defined using this pluviograph. Figure B-9 shows the pluviograph information available at this gauge.

Rainfall depths were estimated by interpolating the AWAP rainfall data to the RORB model subarea centroids. Figure B-9 shows the cumulative rainfall depths across the catchment. Although the overall depth applied to the catchment was determined from the AWAP record, the individual pluviograph records were checked against these values for consistency. Pluviographs were also used for the rainfall temporal patterns.

A summary of the calibration parameters for the April 1935 event are shown in Table B-4 with the hydrograph shown in Figure B-10. Figure B-10 demonstrates that the recorded streamflow data appears to have been observed at relatively coarse intervals. As a result, the shape of the hydrographs is slightly different. However, the overall timing and peak of the hydrograph show a very good match to the recorded April 1935 event.



- **Figure B-9: Cumulative pluviograph record for April 1935 for gauge Macedon Forestry (87036)**

- **Table B-4: Summary of calibration parameter values for April 1935**

Gauge	Name	k_c	m	IL (mm)	CL (mm/h)
230204	Riddells Creek at Riddells Creek	16	0.8	20	3.9

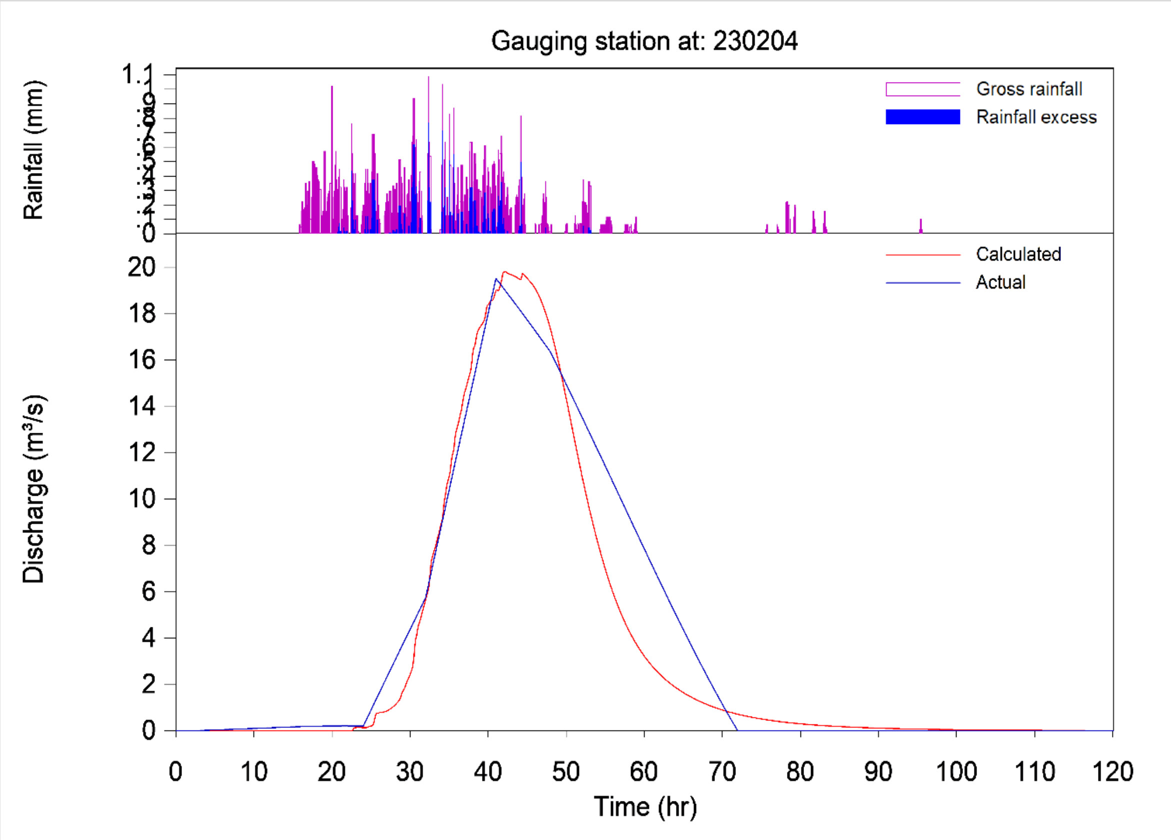
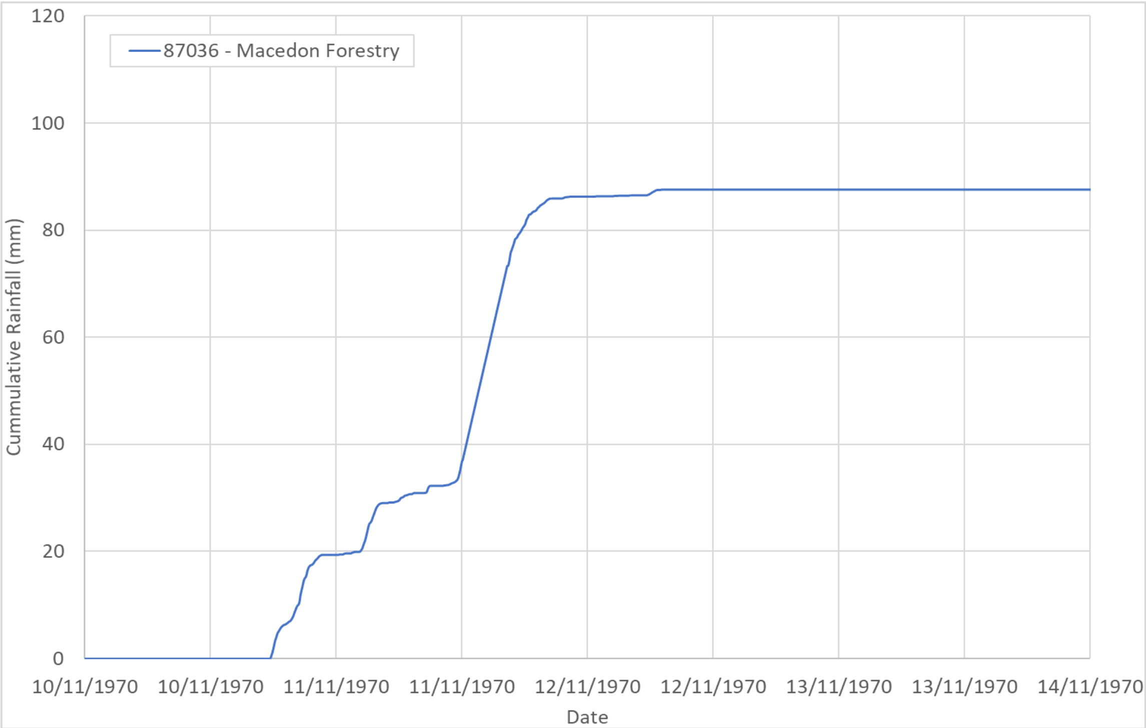


Figure B-10: RORB calibration at Gauge 230204 April 1935 event

November 1970

For the November 1970 event, the closest pluviograph with available information was Macedon Forestry (87036). The temporal pattern of rainfall in each subarea was defined using this pluviograph. Figure B-11 shows the pluviograph information available at this gauge.



- **Figure B-11: Cumulative pluviograph record for November 1970 for gauge Macedon Forestry (87036)**

Rainfall depths were estimated by interpolating the AWAP rainfall data to the RORB model subarea centroids. Although the overall depth applied to the catchment was determined from the AWAP record, the individual pluviograph record was checked against these values for consistency. Pluviographs were also used for the rainfall temporal patterns.

A summary of the calibration parameters for the November 1970 event are shown in Table B-5 with the hydrograph shown in Figure B-12. Figure B-12 highlights from the angular shape of the hydrograph after the peak of the flood event, that there may have been a malfunction at the gauging station just at the peak of the flood event. It also indicates that there was interpolated pluviography data. As a result, the peak flow of the hydrograph is slightly higher than that of the gauging station to be able to match the overall timing, volume and shape of the hydrograph where there appeared to be accurate data for the recorded November 1970 event.

- **Table B-5: Summary of calibration parameter values for November 1970**

Gauge	Name	k_c	m	IL (mm)	CL (mm/h)
230204	Riddells Creek at Riddells Creek	14	0.8	20	6.9

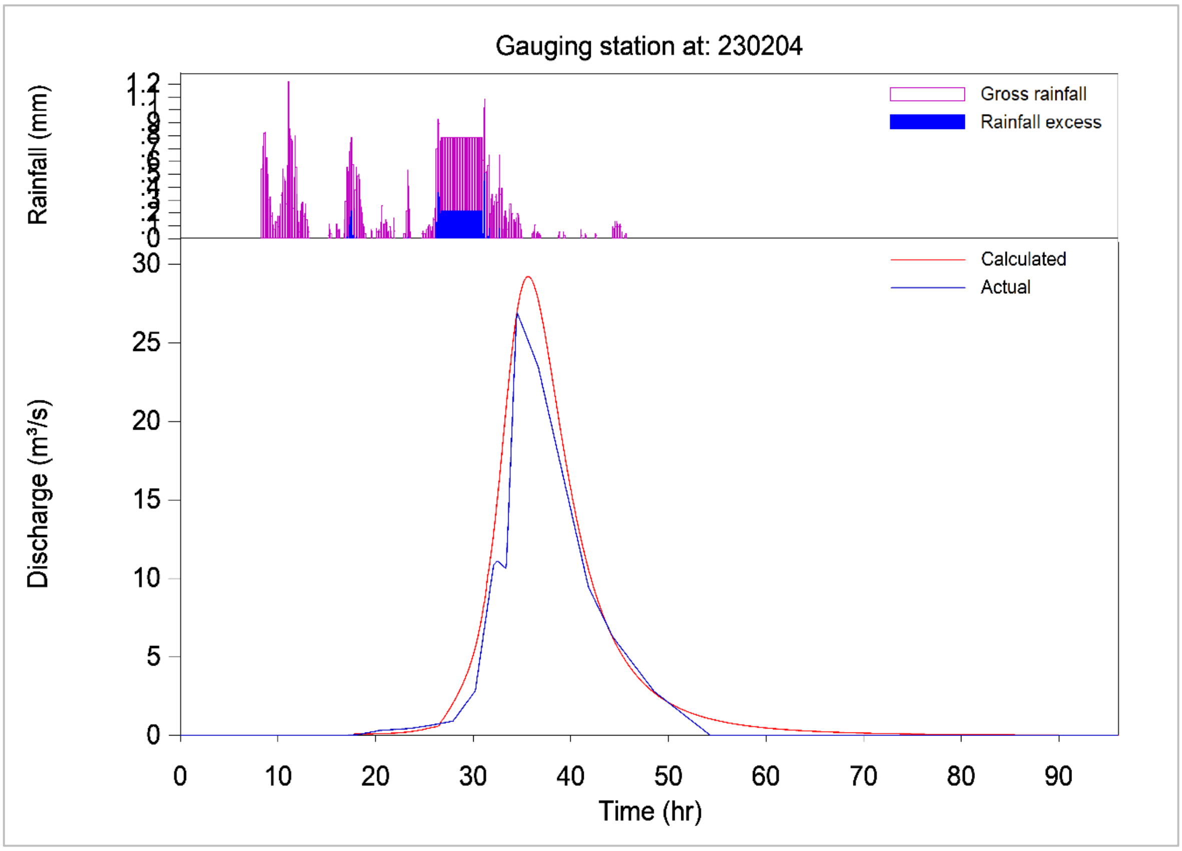


Figure B-12: RORB calibration at Gauge 230204 November 1970 event

B.2.3 Adopted RORB parameter values

In general, the calibration provided a reasonable fit to gauge data that had significant uncertainties associated with it. As with all hydrological modelling the variation between the recorded and modelled hydrograph can be due to a number of things i.e. change in catchment conditions, data errors, baseflow separation error, rainfall variability, rating curve errors and the lack of adequate data to represent the variability across the catchment and the RORB model being only a representation of a variable and complex rainfall runoff process. Table B-6 summarises the k_c values adopted from the calibration process. A k_c of 14 was adopted for design as it provided the most reasonable d_{av}.

Table B-6: Summary of the calibrated k_c values

Gauge	Name	1935	1970	Average / Adopted k_c	d_{av}*	k_c/d_{av}
230204	Riddells Creek at Riddells Creek	16	14	14	12.62	1.11

* d_{av} is the weighted average flow distance to the catchment outlet (this is calculated automatically in the RORB model)

Appendix C Streamflow gauge annual maxima

Table C-1: Wando River at Wando Vale (238223)

Rank	Date	Peak surface runoff (m^3/s)
1	18/09/1978	108.5
2	9/09/2016	87.7
3	8/09/1983	78.3
4	16/10/1976	77.4
5	28/09/1979	67.8
6	23/08/1991	55.1
7	9/10/1992	54.4
8	23/09/1998	43.6
9	26/08/1984	40.2
10	20/01/2007	38.1

Table C-2: Moyne River at Toolong (237200)

Rank	Year	Peak surface runoff (m^3/s)
1	16/10/1976	121.9
2	9/08/1978	119.1
3	23/08/1975	99.6
4	11/08/2010	98.7
5	9/09/1983	97.5
6	20/09/1984	86.1
7	27/07/1977	80.6
8	29/09/1979	73.1
9	10/09/2016	63.2
10	17/08/1981	58.2

Table C-3: Hopkins River at Wickliffe (236202)

Rank	Year	Peak surface runoff (m^3/s)
1	9/09/1983	127.4
2	24/10/1986	102.7
3	22/10/1975	100.3
4	5/09/1964	91.5
5	3/09/1988	90.7
6	7/02/1973	86.3
7	10/08/1981	85.0
8	17/05/1974	83.3
9	21/09/1984	79.7
10	31/08/1992	69.3

Table C-4: Aire River at Wyelangta (235219)

Rank	Year	Peak surface runoff (m^3/s)
1	4/11/2007	241.1
2	4/06/1978	240.9
3	4/06/2012	205.8
4	16/10/1976	202.7
5	22/03/1983	135.6
6	6/11/1995	132.4
7	3/02/2005	124.3
8	11/08/2010	118.8
9	18/09/1984	94.4
10	30/07/1996	88.9

Table C-5: Lerderderg River at Sardine Creek Obrien Crossing (231213)

Rank	Year	Peak surface runoff (m^3/s)
1	24/10/2000	194.4
2	15/05/1974	178.1
3	13/07/1963	132.2
4	15/09/1993	121.6
5	24/10/1985	106.7
6	6/11/1995	95.9
7	7/11/1971	91.8
8	22/09/1976	89.0
9	16/10/1983	84.4
10	12/11/1960	81.6

Table C-6: Riddells Creek at Riddells Creek (230204)

Rank	Year	Peak surface runoff (m^3/s)
1	7/08/1978	31.0
2	11/11/1970	27.8
3	7/11/1971	26.5
4	12/12/1954	22.7
5	21/04/1935	20.9
6	3/04/1950	19.6
7	3/04/1950	19.6
8	15/05/1974	19.1
9	30/11/1934	17.7
10	19/10/1956	17.1

Table C-7: Toomuc Creek at Pakenham (228217)

Rank	Year	Peak surface runoff (m^3/s)
1	5/02/2011	56.1
2	18/09/1984	33.5
3	11/10/1990	31.2
4	3/02/2005	30.6
5	30/07/1996	27.4
6	13/11/2004	26.3
7	29/07/1987	21.0
8	8/11/1985	20.0
9	10/06/1989	19.9
10	12/09/1992	16.2

Table C-8: Moe River at Darnum (226209)

Rank	Year	Peak surface runoff (m^3/s)
1	30/07/1996	58.6
2	5/07/1980	55.3
3	27/10/1989	54.4
4	12/10/1990	50.4
5	28/07/1977	49.5
6	16/09/1993	47.8
7	23/08/1975	46.8
8	19/09/1984	41.2
9	14/09/1983	40.3
10	18/09/1991	39.7

Table C-9: Aberfeldy River at Beardmore (225213)

Rank	Year	Peak surface runoff (m^3/s)
1	28/06/2007	572.2
2	3/06/1978	471.8
3	21/04/1990	357.7
4	15/09/1993	267.7
5	16/10/1976	206.9
6	30/12/1969	159.0
7	8/11/1971	158.7
8	23/10/1995	157.9
9	31/05/1970	156.0
10	3/02/2005	136.4

Table C-10: Macalister River at Stringybark Creek (225221)

Rank	Year	Peak surface runoff (m³/s)
1	27/06/2007	2173.8
2	5/06/2012	728.2
3	22/04/1990	598.6
4	8/11/1971	509.6
5	11/08/2011	500.6
6	16/09/1993	499.5
7	25/10/1985	457.7
8	31/05/1970	427.6
9	14/06/1978	418.7
10	18/07/1974	408.7

Table C-11: Traralgon Creek at Traralgon (226023)

Rank	Year	Peak surface runoff (m³/s)
1	4/06/1978	368.8
2	15/09/1993	230.4
3	6/11/1995	193.8
4	31/05/1969	74.0
5	27/10/1989	66.4
6	23/04/2001	61.6
7	7/07/1983	48.2
8	27/12/1968	47.8
9	31/05/1970	47.6
10	29/06/1980	40.7

Table C-12: Mitchell River at Glenaladale (224203)

Rank	Year	Peak surface runoff (m³/s)
1	12/12/1952	1149.4
2	30/01/1971	1108.8
3	31/05/1970	978.1
4	21/09/1959	854.5
5	3/06/1978	819.0
6	20/07/1949	789.4
7	29/08/1974	781.5
8	6/04/1950	712.9
9	25/11/1942	679.4
10	22/08/1951	653.2

Table C-13: Avoca River at Coonooer (408200)

Rank	Year	Peak surface runoff (m^3/s)
1	5/09/2010	673.1
2	5/08/1981	362.2
3	10/06/1995	352.6
4	7/02/1973	351.0
5	9/10/1975	349.9
6	1/10/1996	313.1
7	9/09/1983	310.9
8	15/01/1974	298.9
9	9/10/1992	295.7
10	4/09/1988	266.9

Table C-14: Tullaroop Creek at Clunes (407222)

Rank	Year	Peak surface runoff (m^3/s)
1	14/01/2011	573.6
2	4/09/2010	544.0
3	14/09/2016	315.6
4	18/09/1975	179.3
5	15/05/1974	175.0
6	24/10/2000	169.2
7	4/08/1981	137.0
8	8/09/1983	134.4
9	19/09/1993	132.2
10	28/09/1979	131.0

Table C-15: Loddon River at Newstead (407215)

Rank	Year	Peak surface runoff (m^3/s)
1	14/01/2011	720.5
2	14/09/2016	611.5
3	27/11/2010	575.9
4	24/10/2000	571.0
5	20/09/1993	310.7
6	9/06/1995	290.9
7	18/07/1990	275.0
8	1/10/1996	274.4
9	18/09/1975	271.6
10	8/09/1983	248.7

Table C-16: Campaspe River at Redesdale (406213)

Rank	Year	Peak surface runoff (m^3/s)
1	17/09/1975	422.3
2	14/09/2016	347.9
3	14/01/2011	322.1
4	4/09/2010	259.6
5	18/07/1990	228.2
6	7/08/1978	216.2
7	8/09/1983	188.9
8	28/09/1979	180.4
9	15/09/1993	179.0
10	24/10/2000	178.4

Table C-17: Major Creek at Graytown (405248)

Rank	Year	Peak surface runoff (m^3/s)
1	5/10/1974	250.1
2	6/10/1979	178.2
3	17/10/1992	140.8
4	20/10/1973	137.2
5	8/09/1983	133.9
6	25/10/1975	108.0
7	23/10/1986	95.1
8	4/08/1981	93.6
9	28/11/2010	87.6
10	9/06/1995	79.0

Table C-18: Pranjip Creek at Moorilim (405226)

Rank	Year	Peak surface runoff (m^3/s)
1	16/05/1974	201.9
2	5/10/1993	176.0
3	19/09/1975	105.2
4	31/07/1983	97.2
5	23/07/1981	88.3
6	19/10/1992	88.1
7	1/03/2012	85.4
8	6/09/2010	84.2
9	10/06/1995	84.1
10	1/10/1979	82.2

Table C-19: Acheron River at Taggerty (405209)

Rank	Year	Peak surface runoff (m^3/s)
1	5/09/2010	293.7
2	1/10/1996	184.3
3	25/06/1994	167.0
4	15/05/1974	148.1
5	29/06/1980	123.4
6	2/09/1993	95.4
7	31/08/2005	93.4
8	9/06/1995	87.5
9	23/09/1998	86.8
10	3/10/1984	82.8

Table C-20: Ford Creek at Mansfield (405245)

Rank	Year	Peak surface runoff (m^3/s)
1	18/09/1975	234.9
2	8/12/2010	175.6
3	4/10/1993	167.1
4	23/08/1970	94.3
5	9/06/1995	81.6
6	17/10/1992	80.4
7	18/07/1990	72.5
8	27/09/1978	71.1
9	31/08/2005	68.9
10	1/10/1996	68.2

Table C-21: Delatite River at Tonga Bridge (405214)

Rank	Year	Peak surface runoff (m^3/s)
1	18/09/1975	468.7
2	4/10/1993	277.4
3	17/10/1992	226.9
4	1/10/1996	186.4
5	27/09/1964	171.6
6	24/08/1970	164.5
7	27/09/1978	153.2
8	9/06/1995	145.7
9	15/08/1958	145.2
10	23/09/1998	142.6

Table C-22: Boosey Creek at Tungamah (404204)

Rank	Year	Peak surface runoff (m^3/s)
1	2/03/2012	269.6
2	6/10/1993	177.6
3	11/12/2010	107.9
4	19/07/1995	44.1
5	3/10/2016	40.8
6	6/02/2005	38.8
7	27/09/1992	38.5
8	7/02/2011	35.3
9	20/09/1986	33.1
10	8/07/1990	32.1

Table C-23: Holland Creek at Kelfeera (404207)

Rank	Year	Peak surface runoff (m^3/s)
1	4/10/1993	700.0
2	15/05/1974	360.8
3	14/12/1966	320.0
4	21/07/1981	277.4
5	23/09/1998	238.1
6	18/09/1975	193.9
7	4/10/1984	186.2
8	4/06/1968	175.3
9	27/09/1978	159.9
10	1/10/1996	159.2

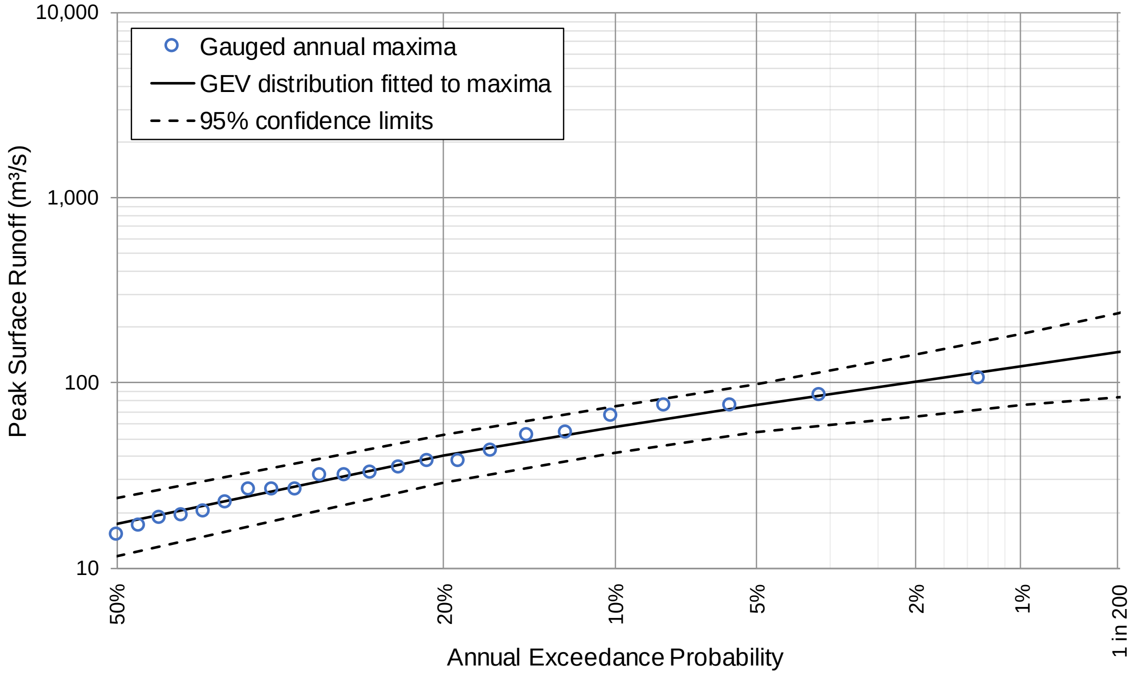
Table C-24: Buffalo River at Abbeyard (403222)

Rank	Year	Peak surface runoff (m^3/s)
1	23/09/1998	227.7
2	15/05/1974	170.8
3	4/09/2010	165.7
4	4/10/1993	150.3
5	1/10/1996	114.1
6	24/07/1981	95.7
7	4/07/1986	90.5
8	18/09/1975	83.1
9	5/07/1990	81.7
10	28/08/1970	80.1

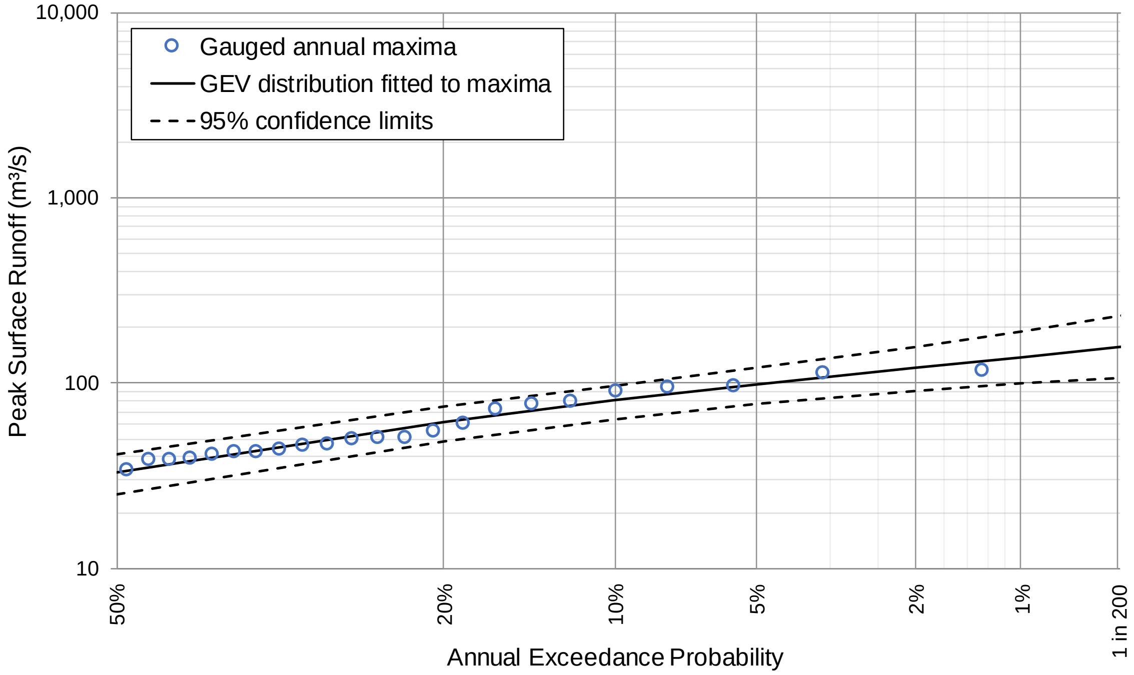
Table C-25: Mitta Mitta River at Hinnomunjie (401203)

Rank	Year	Peak surface runoff (m^3/s)
1	1/11/1974	347.9
2	18/09/1975	340.9
3	24/08/1954	338.6
4	8/11/1971	334.5
5	30/08/1932	313.6
6	17/04/1956	278.2
7	7/10/1968	276.4
8	23/09/1955	273.8
9	16/08/1958	217.3
10	21/09/1959	203.8

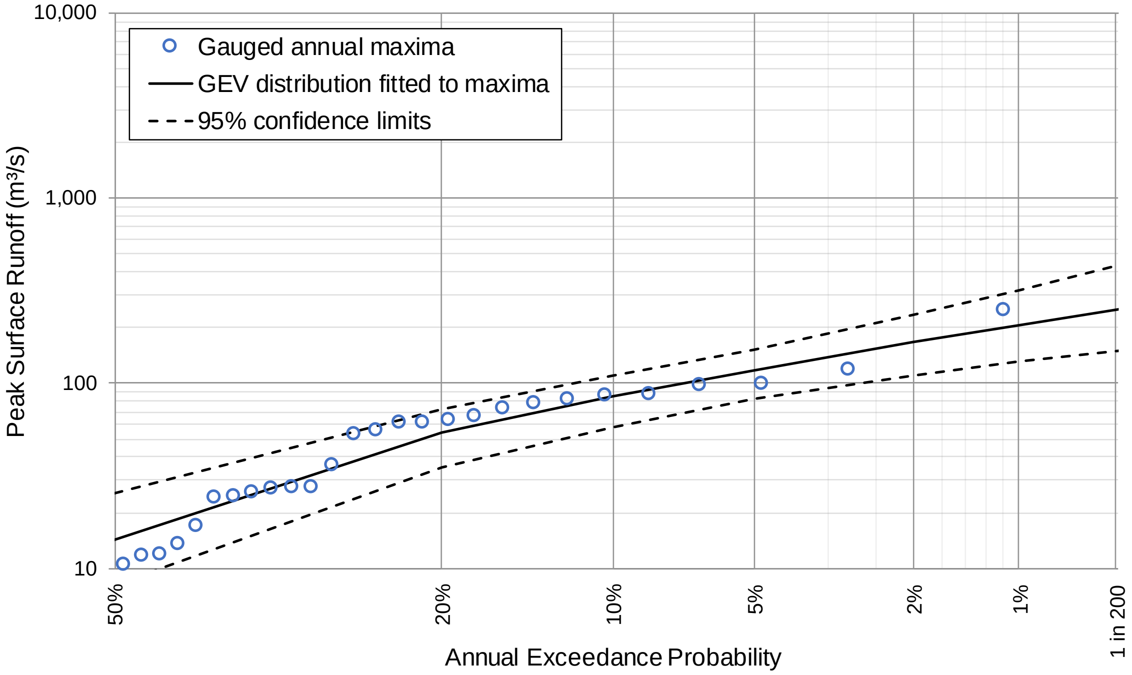
Appendix D Flood frequency analyses



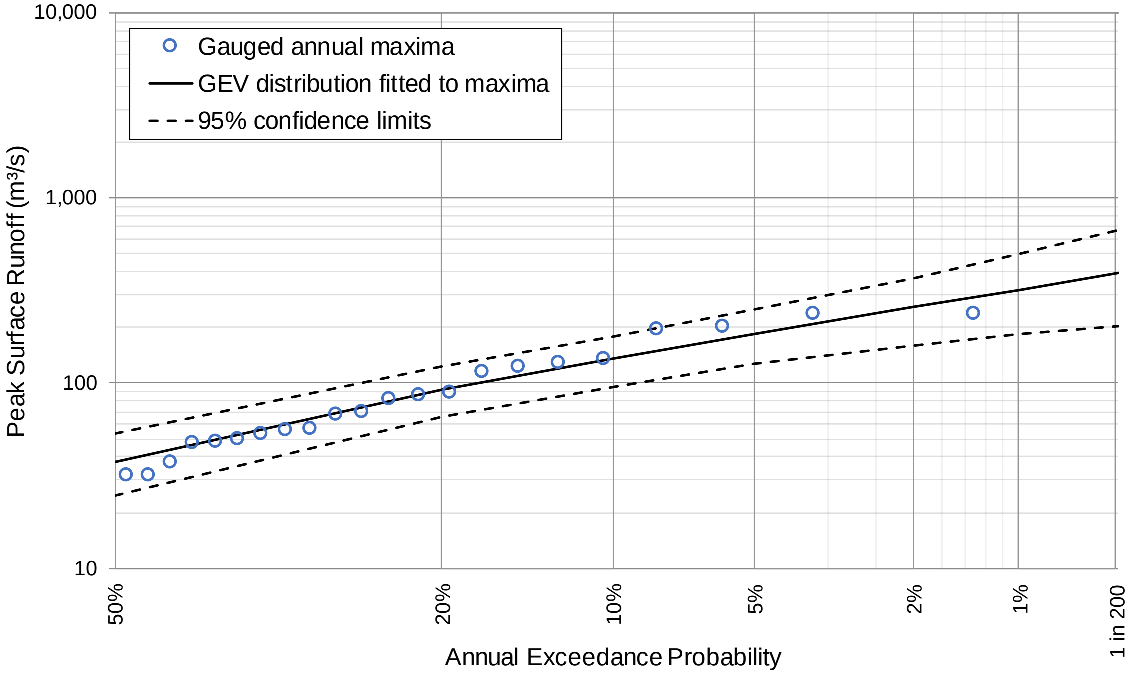
- **Figure D-1: Wando River at Wando Vale (238223)**



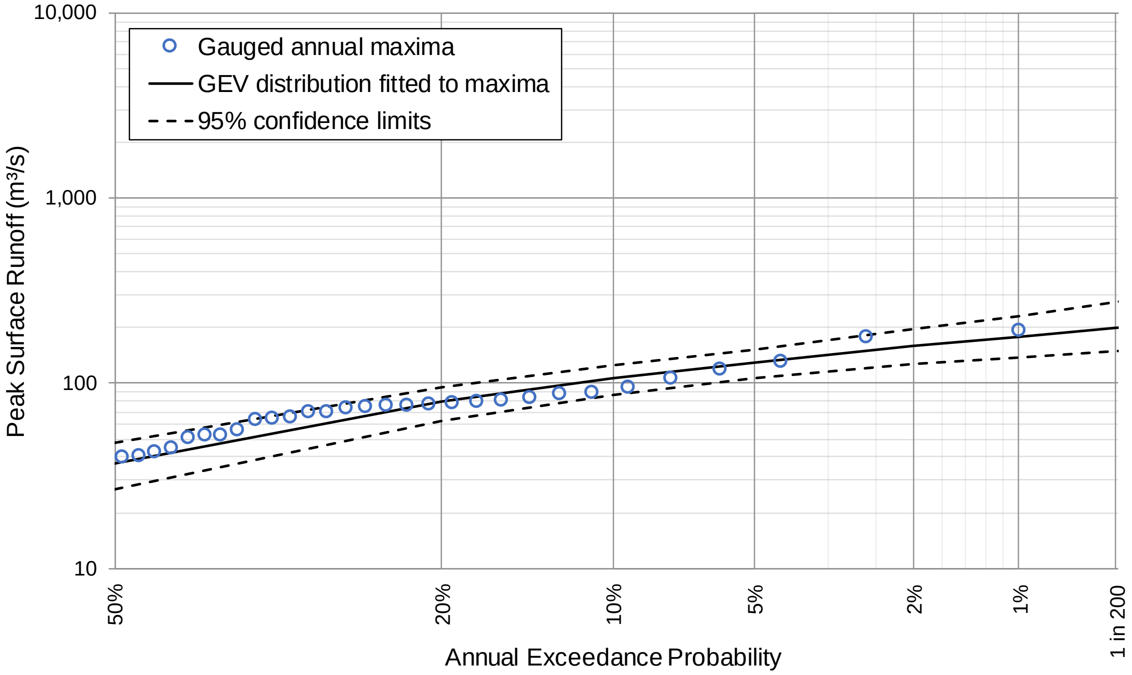
- **Figure D-2: Moyne River at Toolong (237200)**



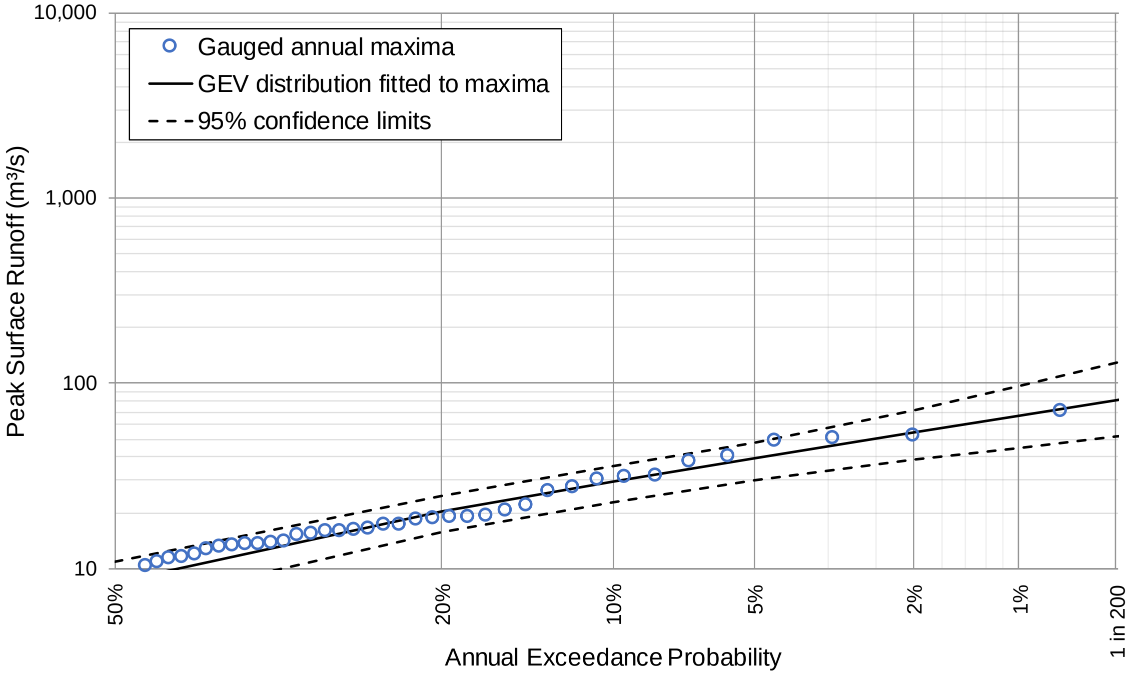
■ **Figure D-3: Hopkins River at Wickliffe (236202)**



■ **Figure D-4: Aire River at Wyelangta (235219)**



■ **Figure D-5: Lerderderg River at Sardine Creek Obrien Crossing (231213)**



■ **Figure D-6: Riddells Creek at Riddells Creek (230204)**

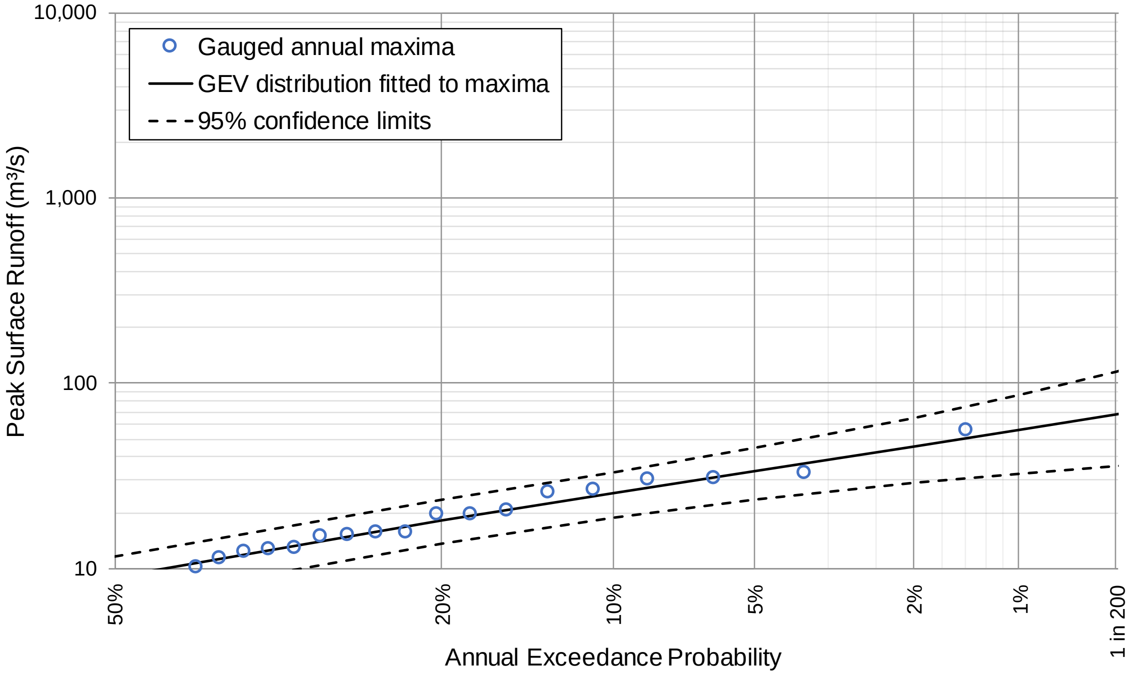


Figure D-7: Toomuc Creek at Pakenham (228217)

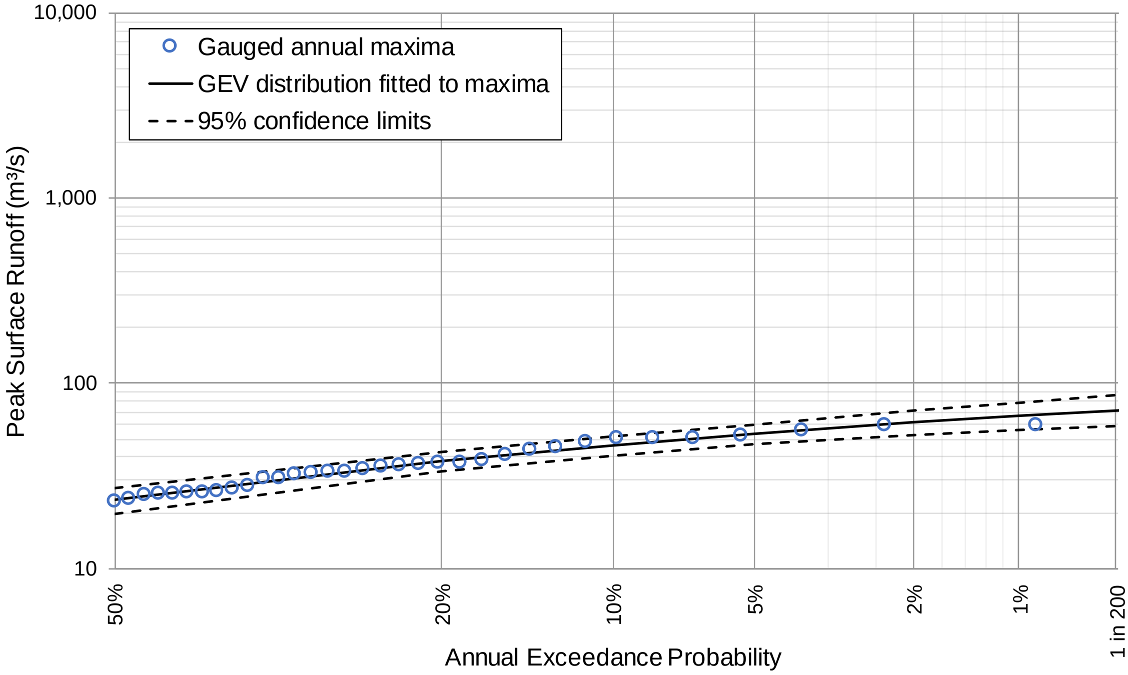
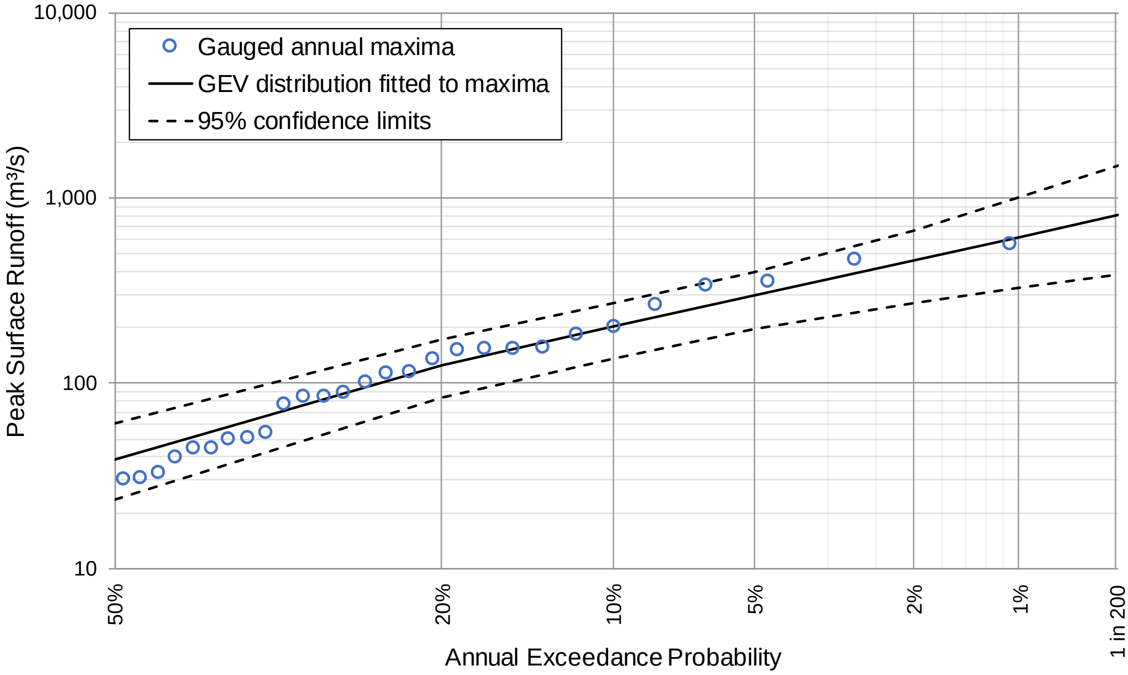
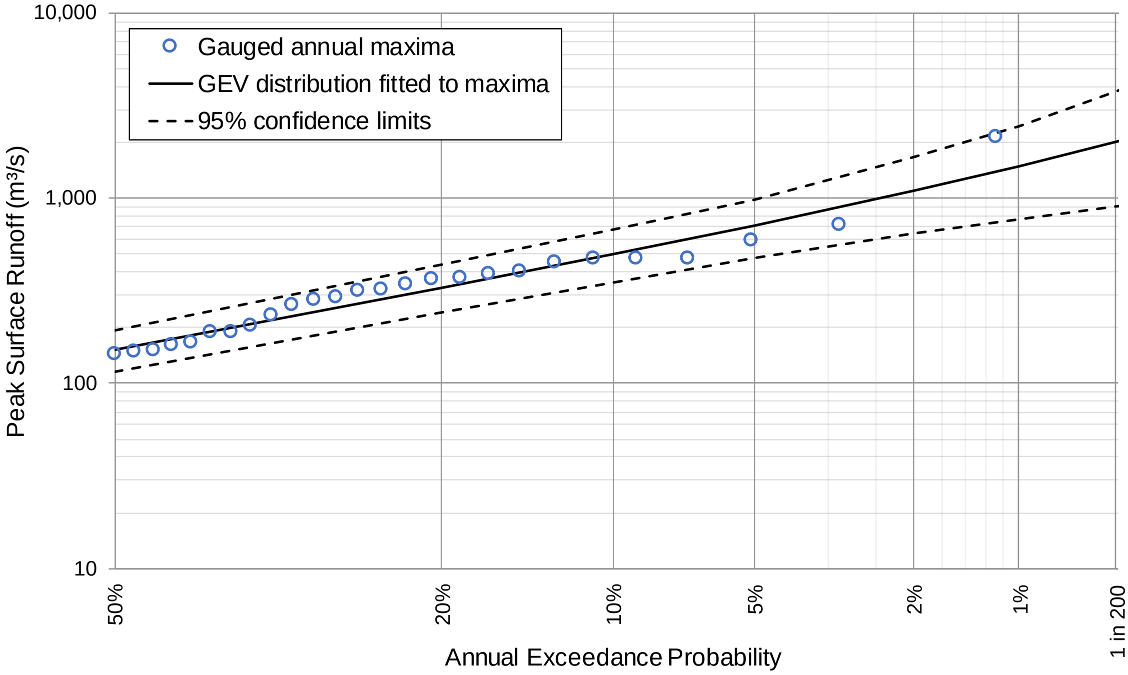


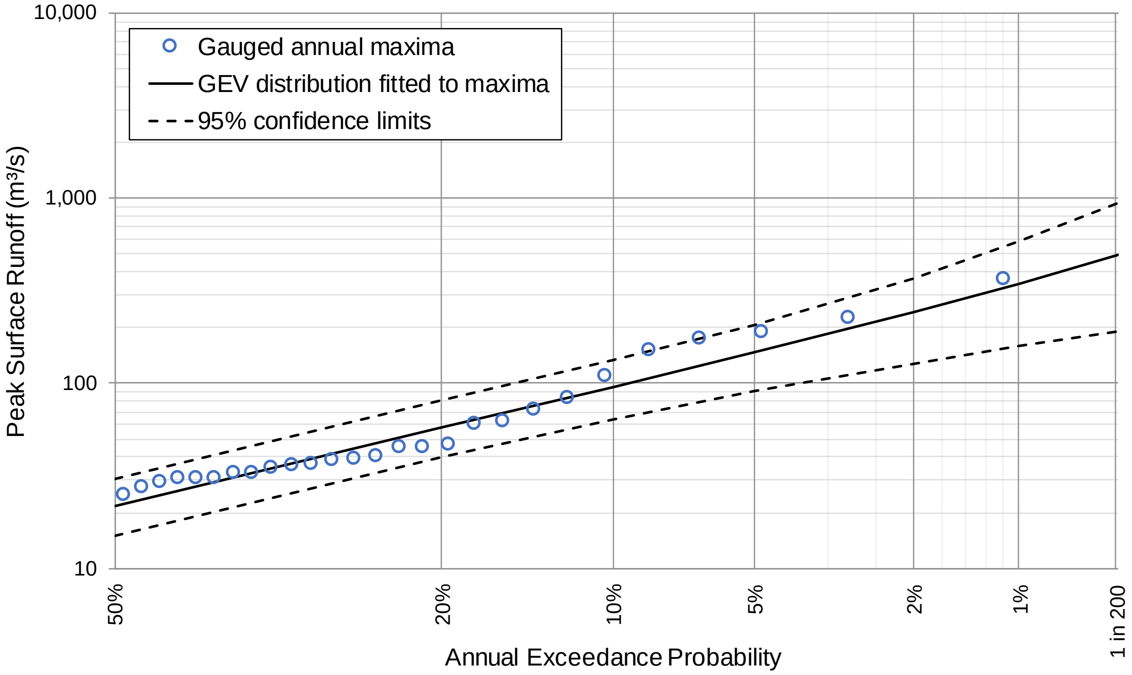
Figure D-8: Moe River at Darnum (226209)



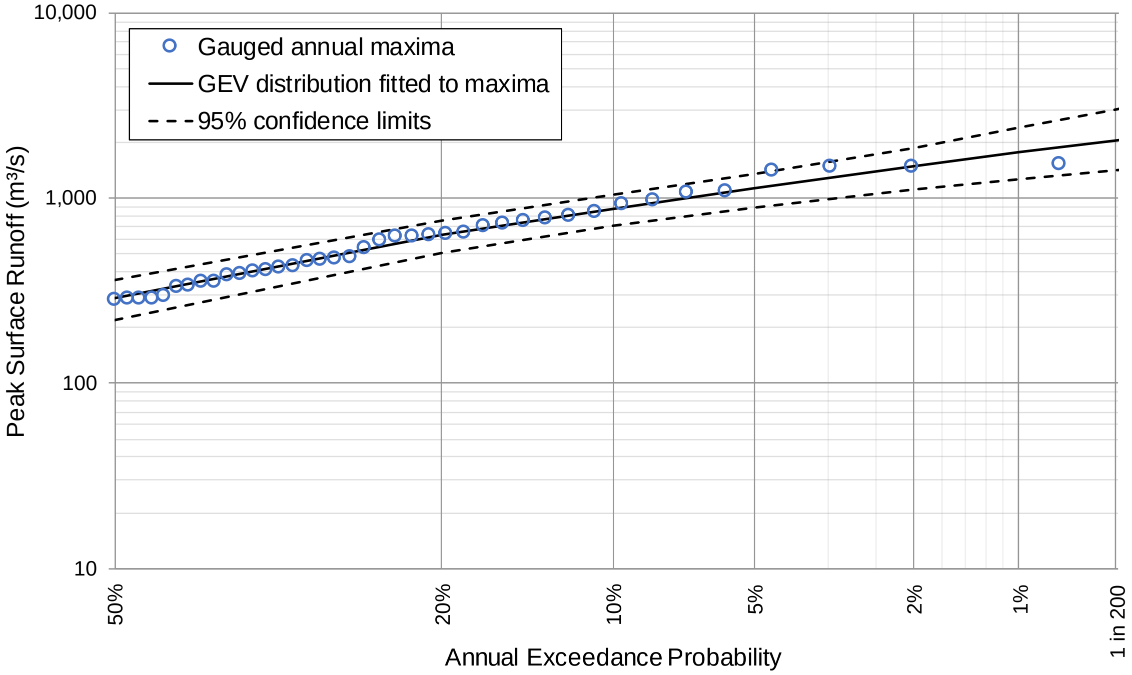
■ **Figure D-9: Aberfeldy River at Beardmore (225213)**



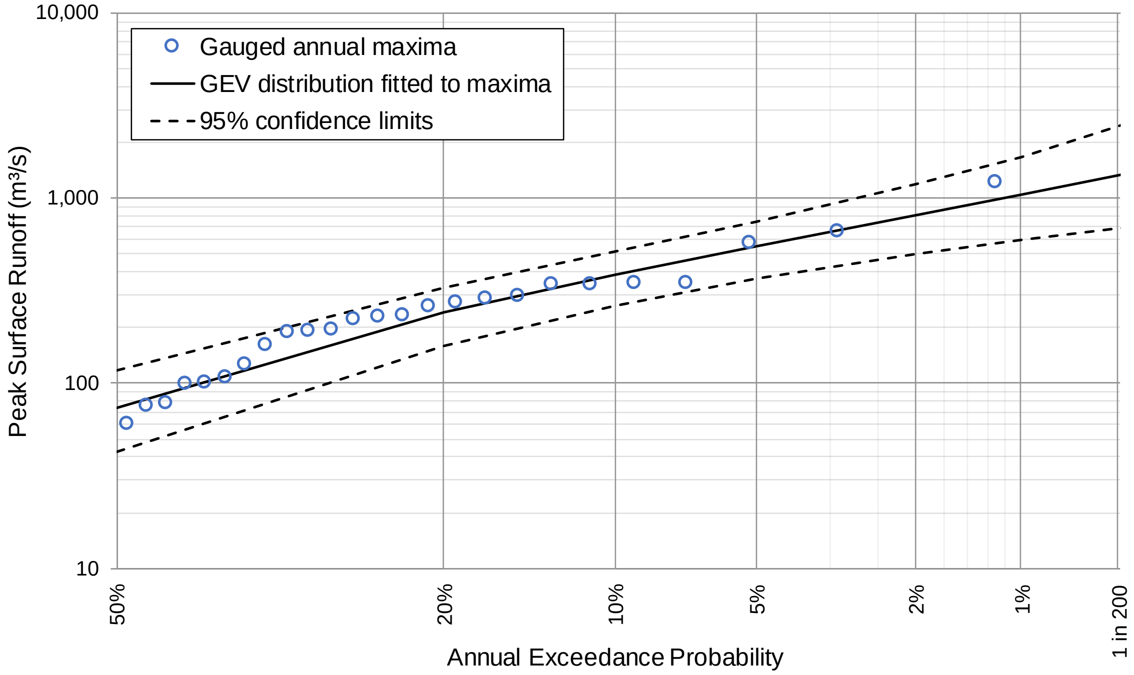
■ **Figure D-10: Macalister River at Stringybark Creek (225221)**



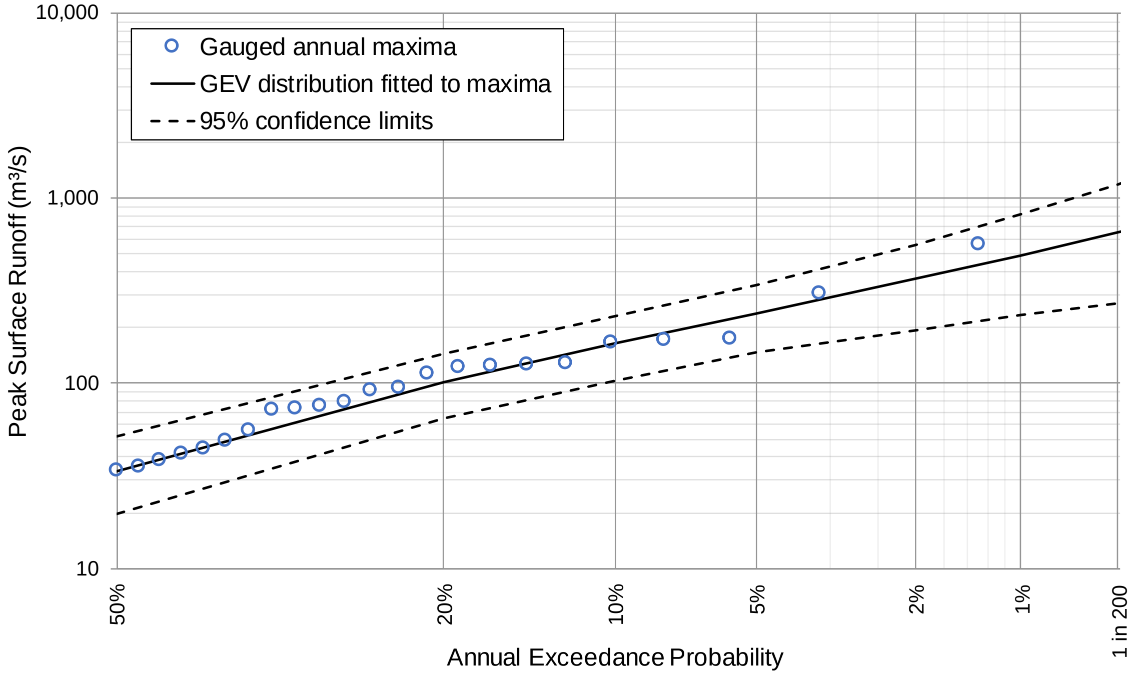
■ **Figure D-11: Traralgon Creek at Traralgon (226023)**



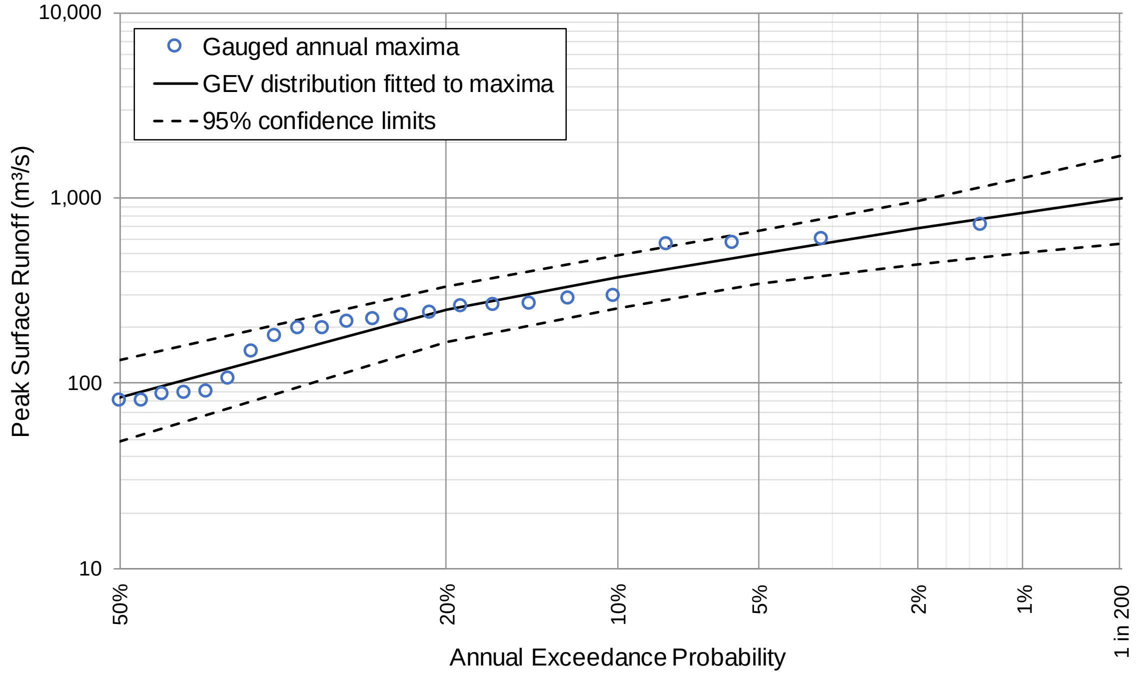
■ **Figure D-12: Mitchell River at Glenaladale (224203)**



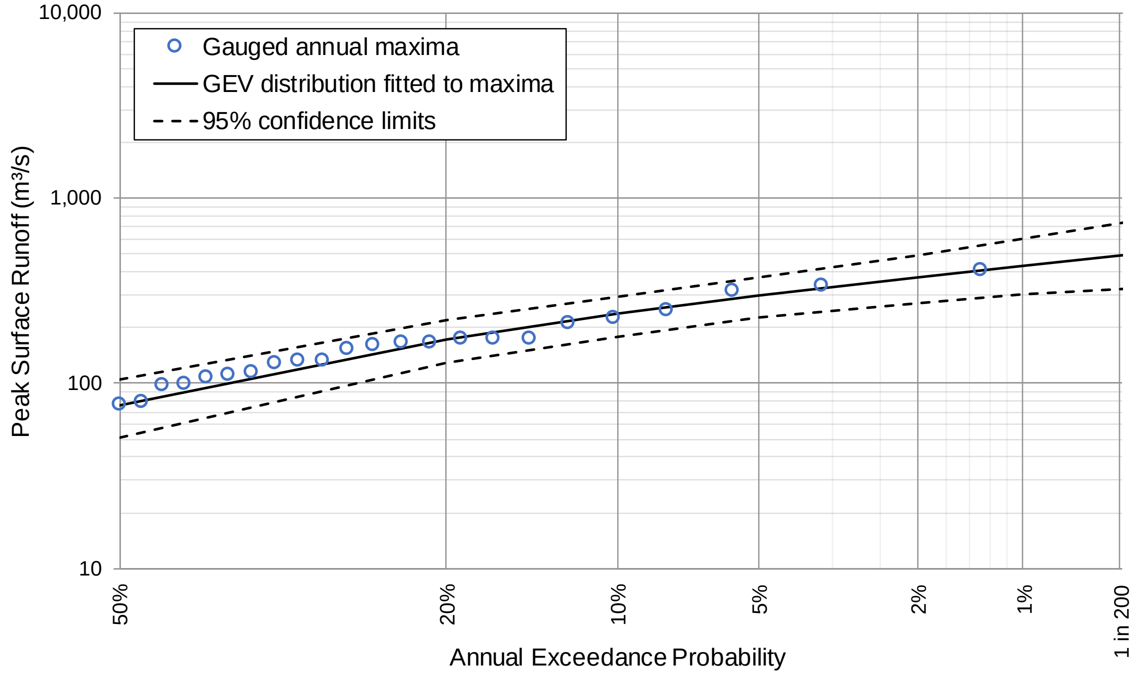
■ **Figure D-13: Avoca River at Coonooer (408200)**



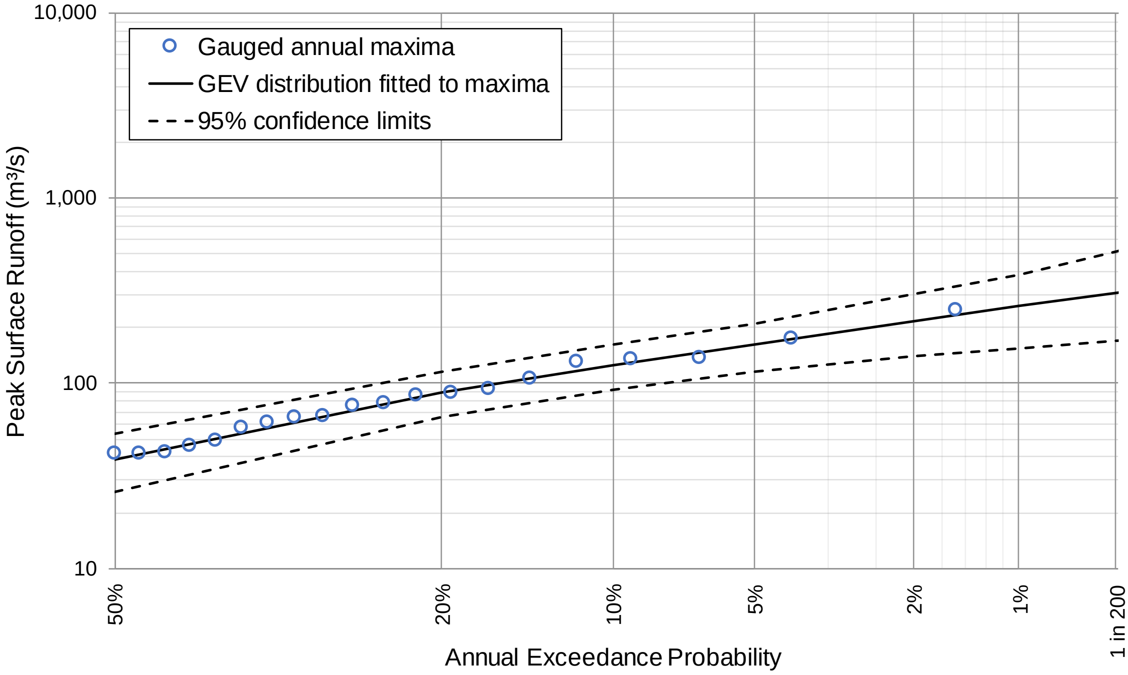
■ **Figure D-14: Tullaroop Creek at Clunes (407222)**



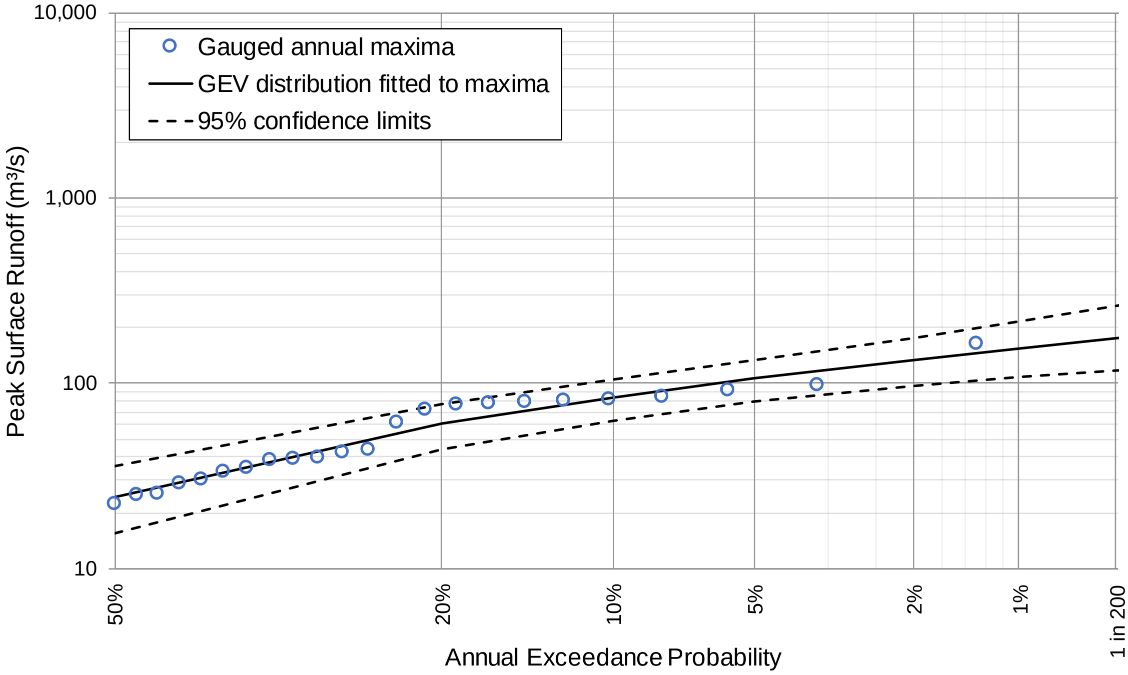
■ **Figure D-15: Loddon River at Newstead (407215)**



■ **Figure D-16: Campaspe River at Redesdale (406213)**



■ **Figure D-17: Major Creek at Graytown (405248)**



■ **Figure D-18: Pranjip Creek at Moorilim (405226)**

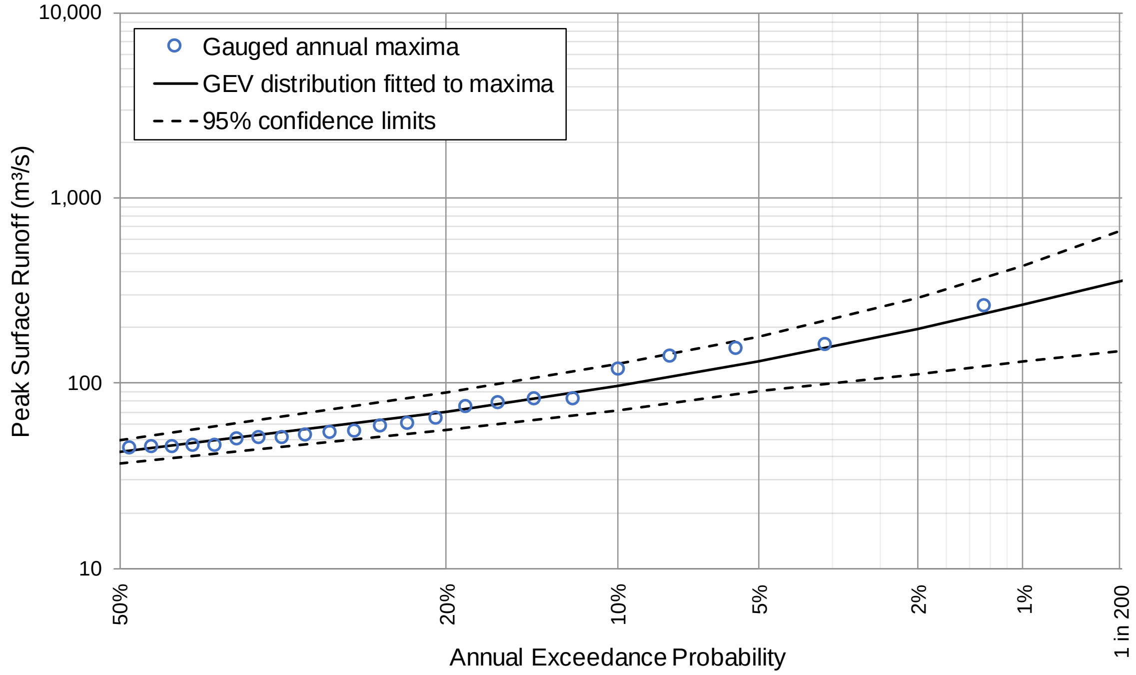


Figure D-19: Acheron River at Taggerty (405209)

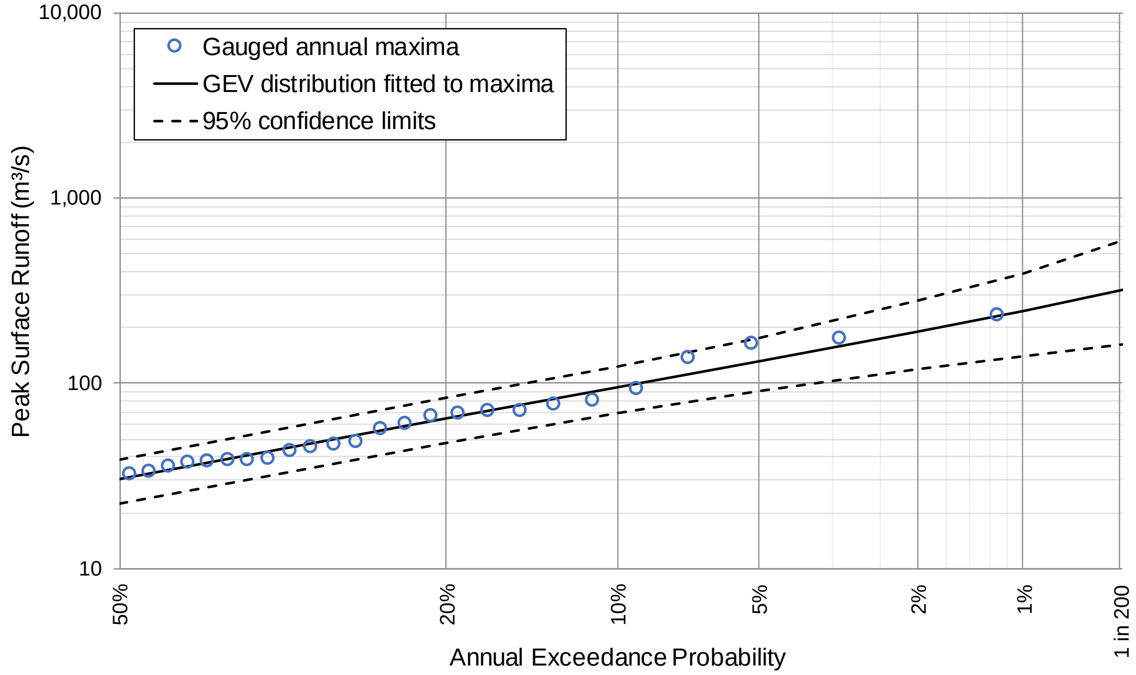
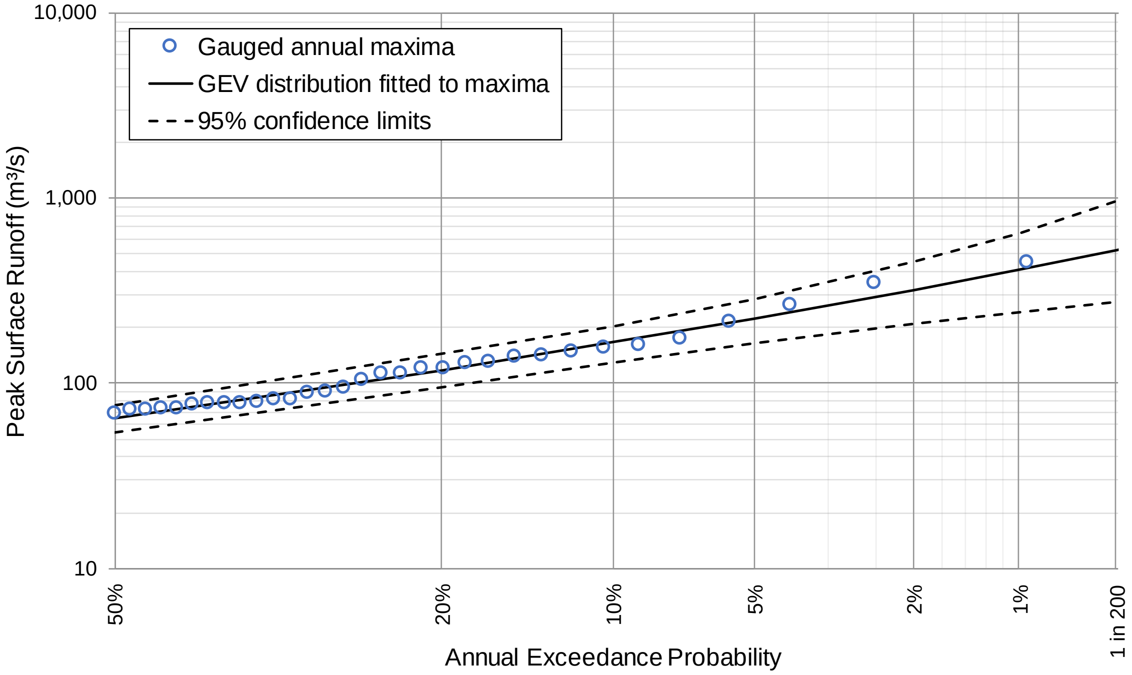
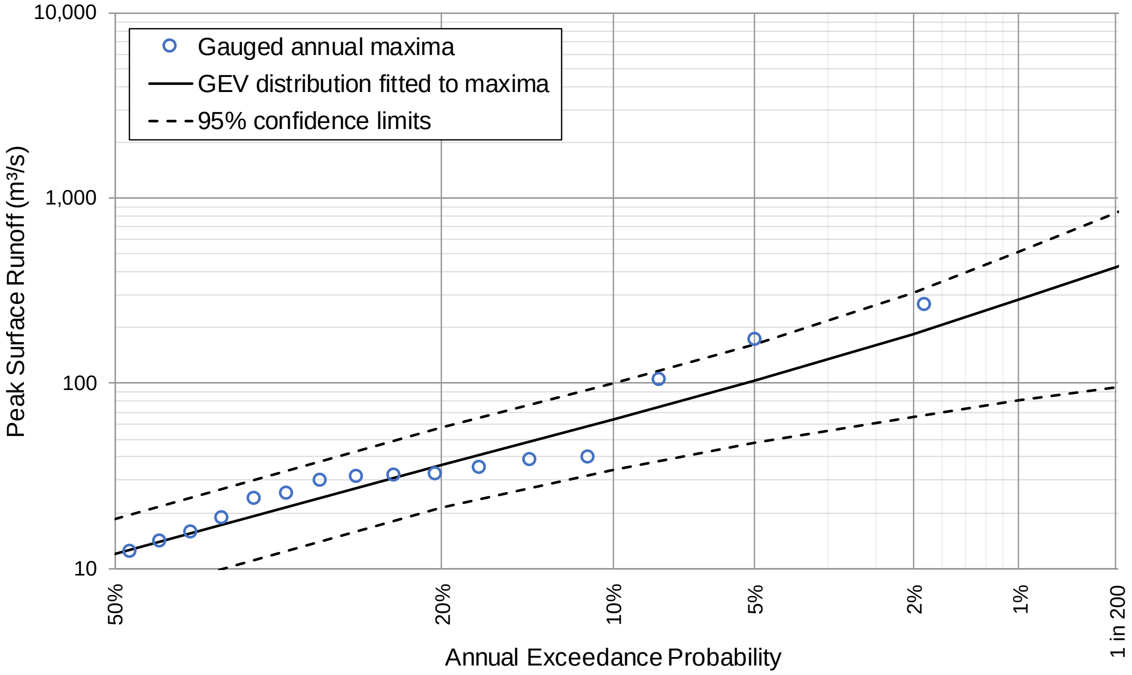


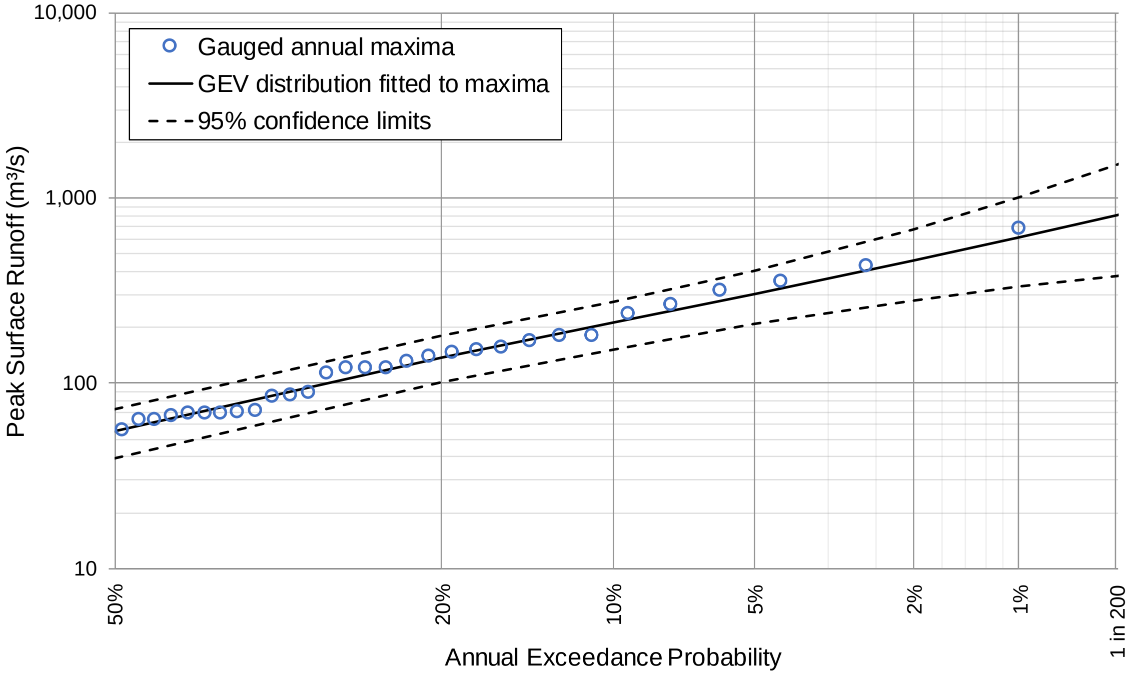
Figure D-20: Ford Creek at Mansfield (405245)



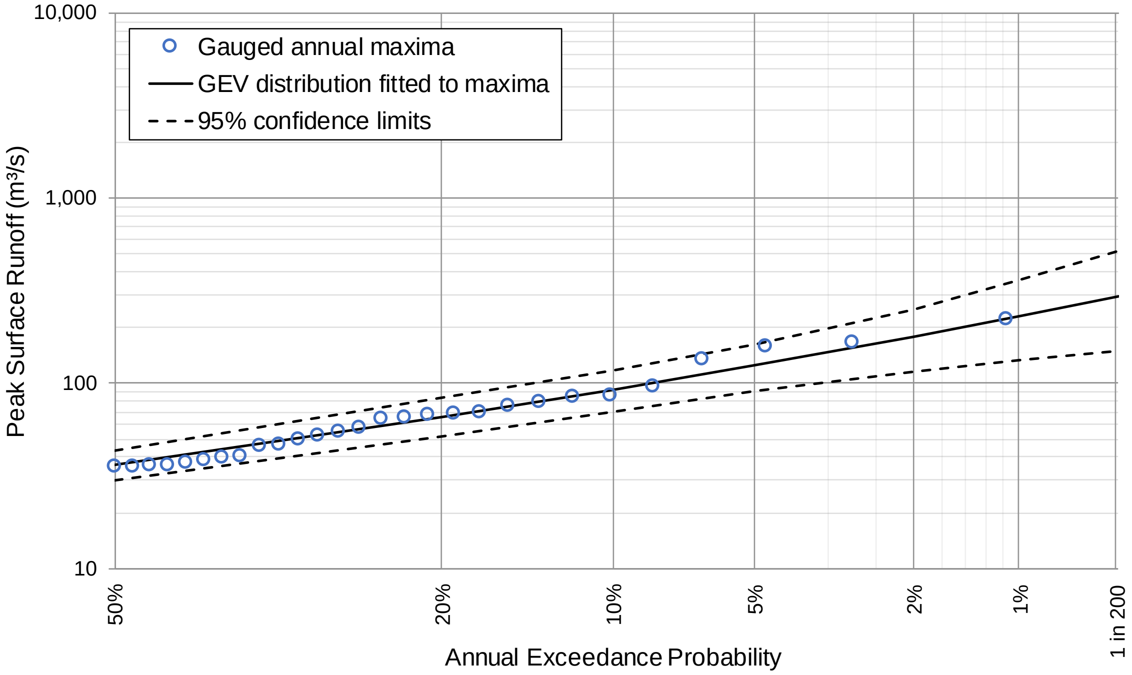
▪ **Figure D-21: Delatite River at Tonga Bridge (405214)**



▪ **Figure D-22: Boosey Creek at Tungamah (404204)**



- **Figure D-23: Holland Creek at Kelfeera (404207)**



- **Figure D-24: Buffalo River at Abbeyard (403222)**

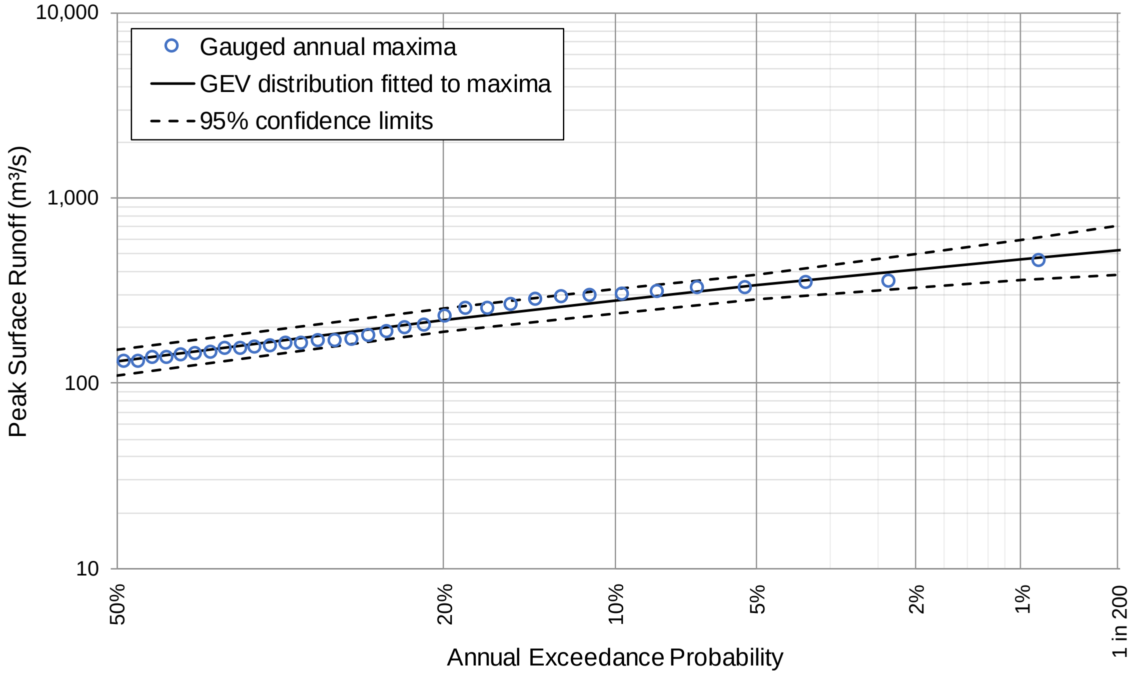
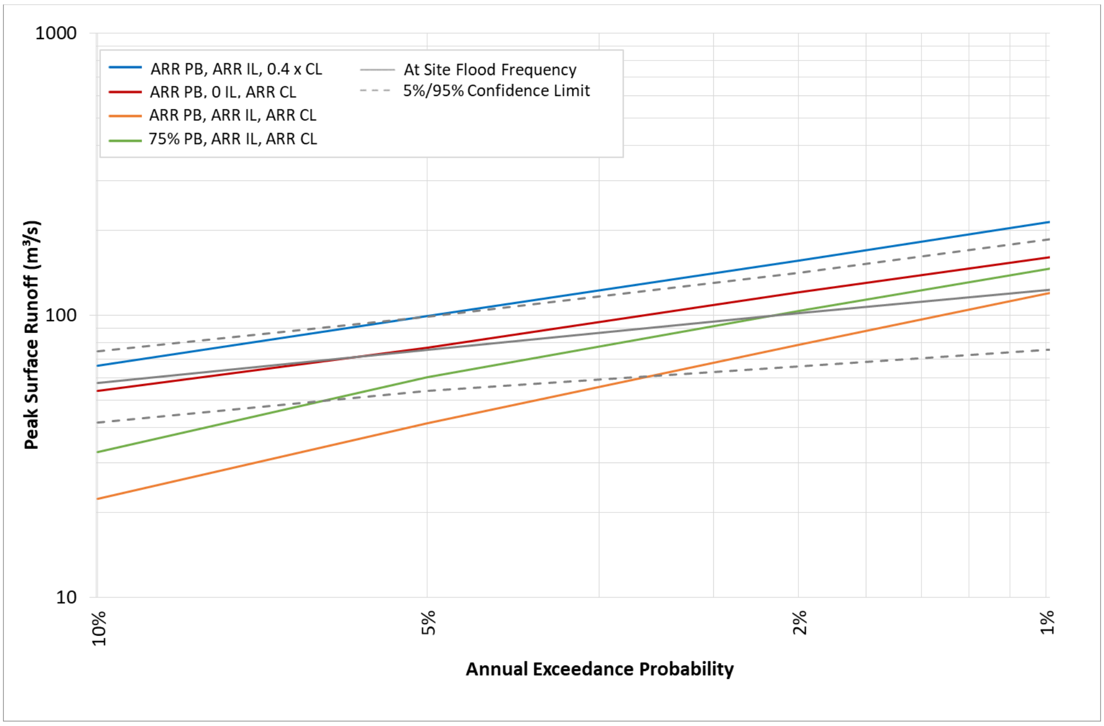
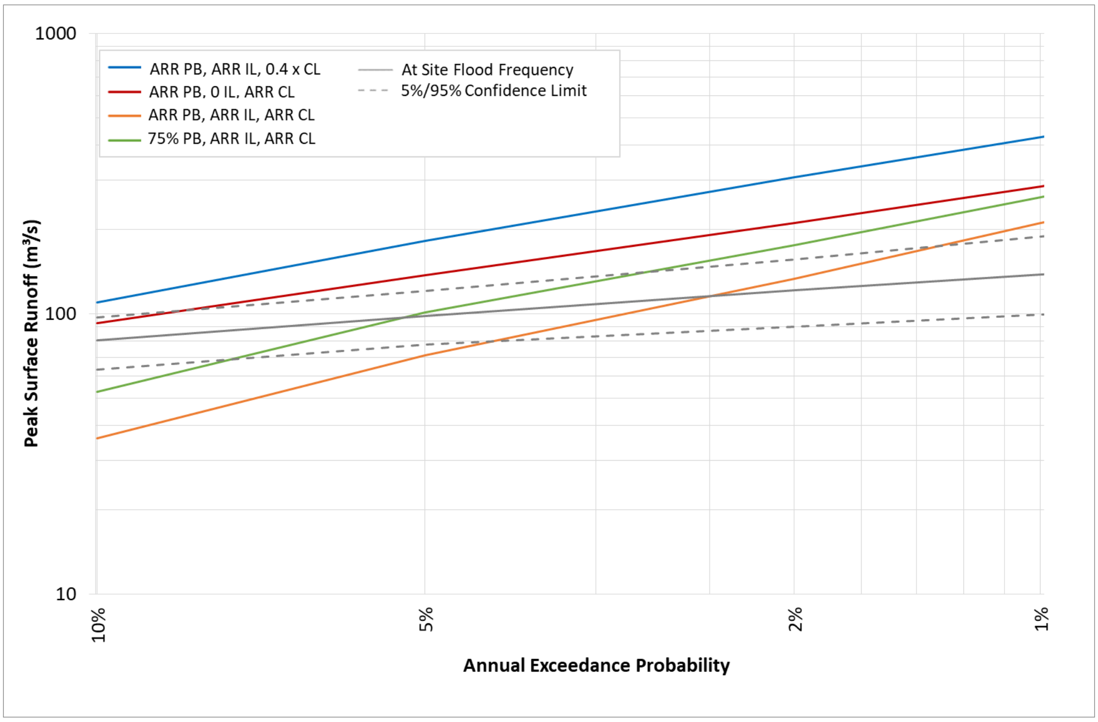


Figure D-25: Mitta Mitta River at Hinnomunjie (401203)

Appendix E Individual catchment benchmarking results



■ Figure E-1 Wando River at Wando Vale (238223)



■ Figure E-2 : Moyne River at Toolong (237200)

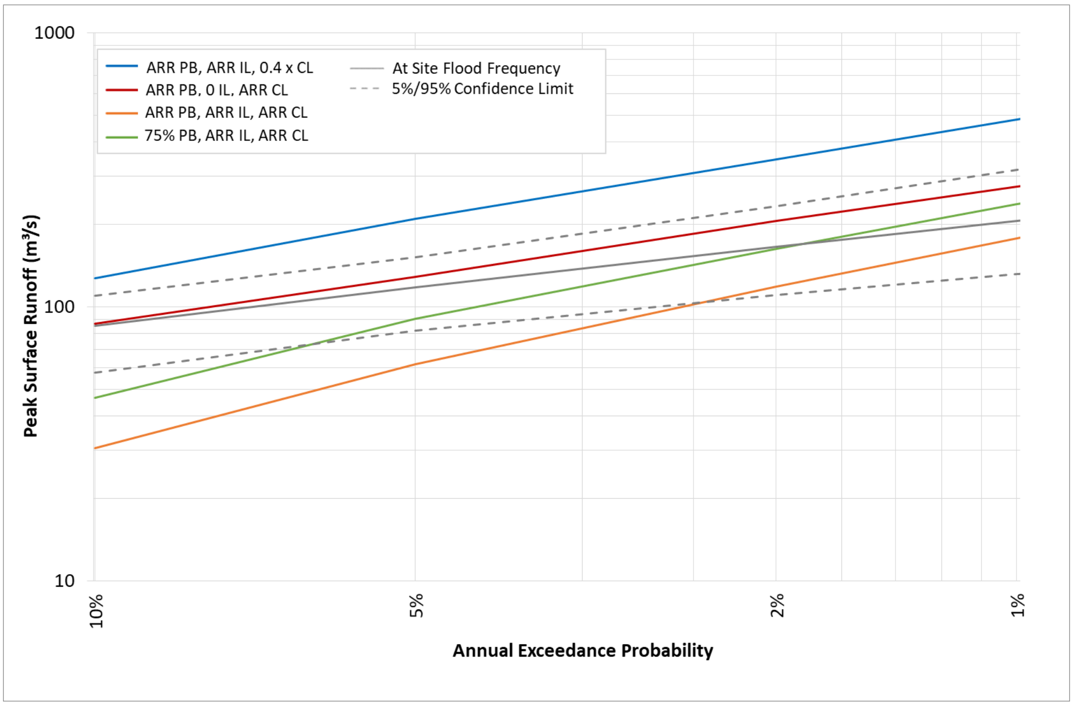


Figure E-3: Hopkins River at Wickliffe (236202)

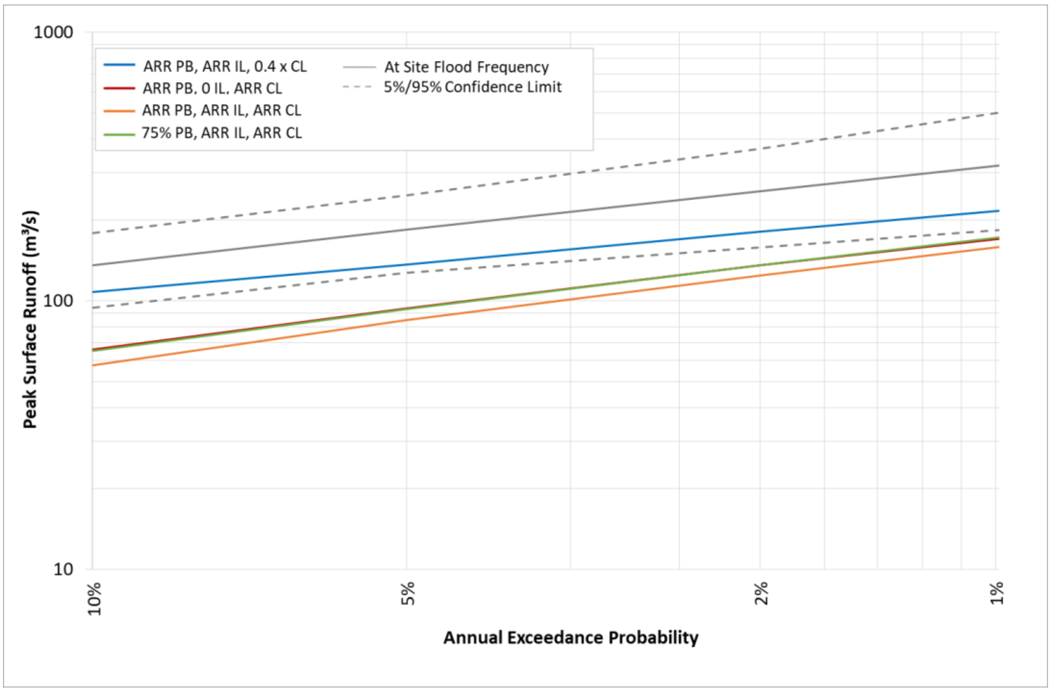
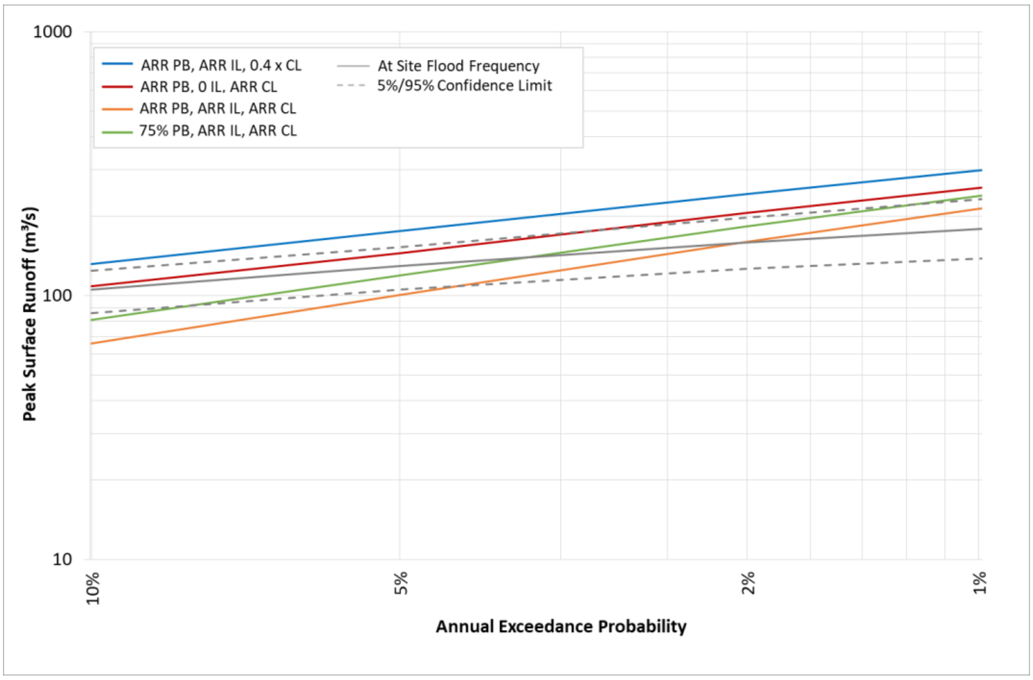
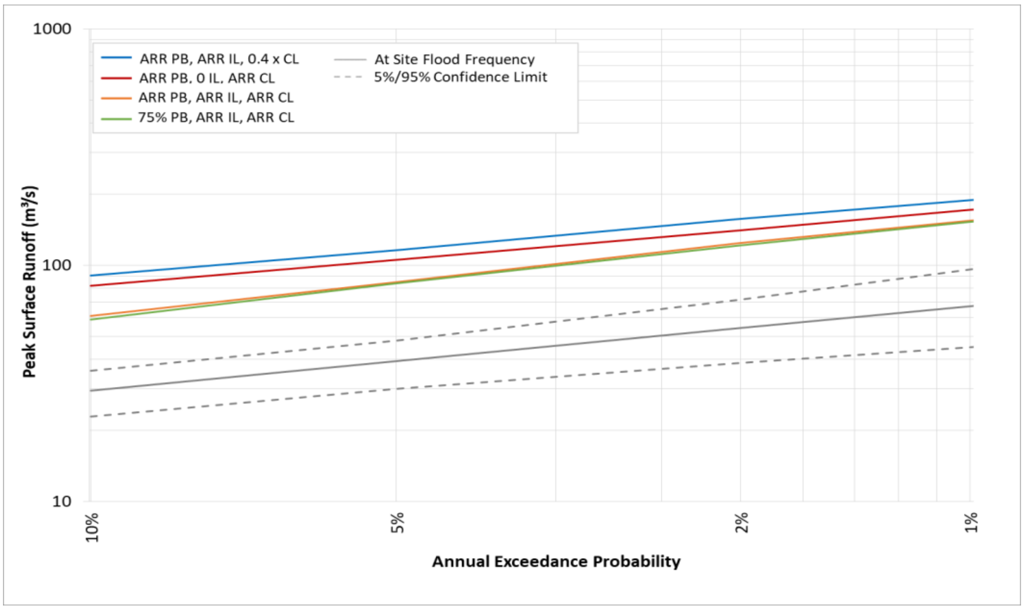


Figure E-4: Aire River at Wyelangta (235219)



■ **Figure E-5: Lerderderg River at Sardine Creek Obrien Crossing (231213)**



■ **Figure E-6: Riddells Creek at Riddells Creek (230204)**

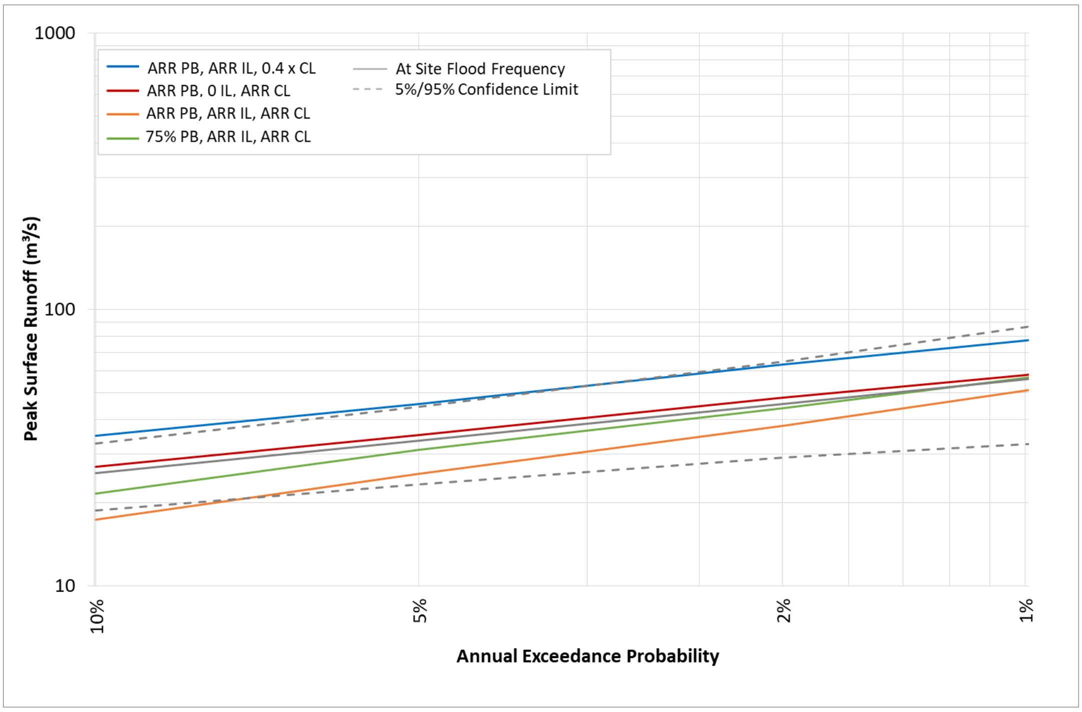


Figure E-7: Toomuc Creek at Pakenham (228217C)

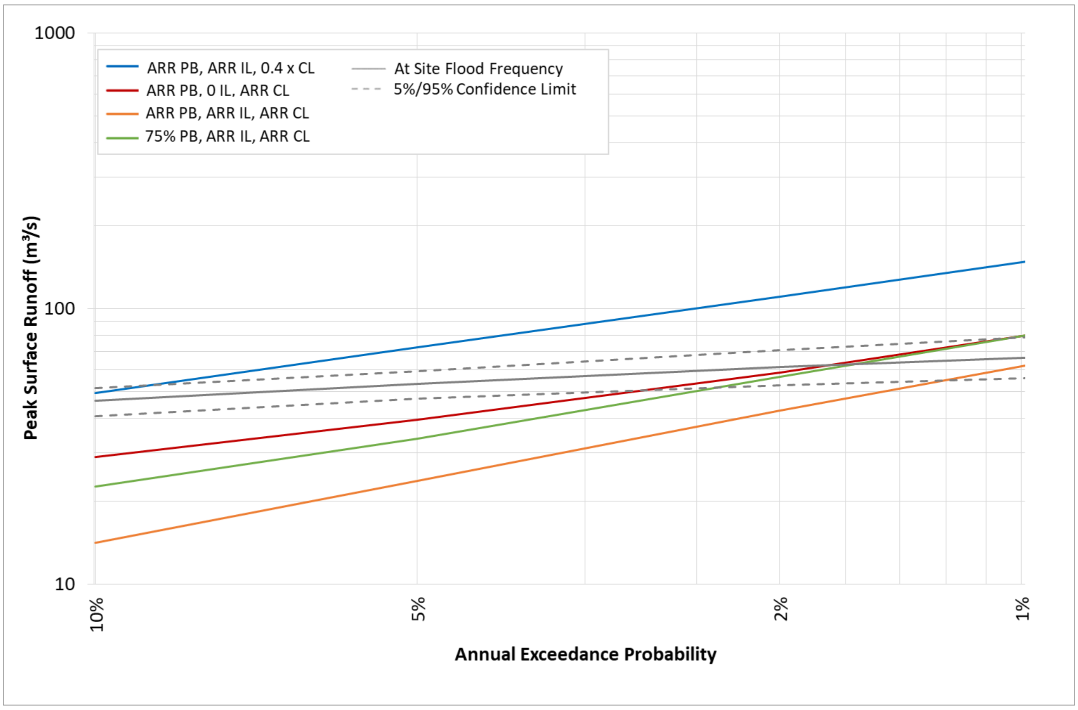


Figure E-8: Moe River at Darnum (226209)

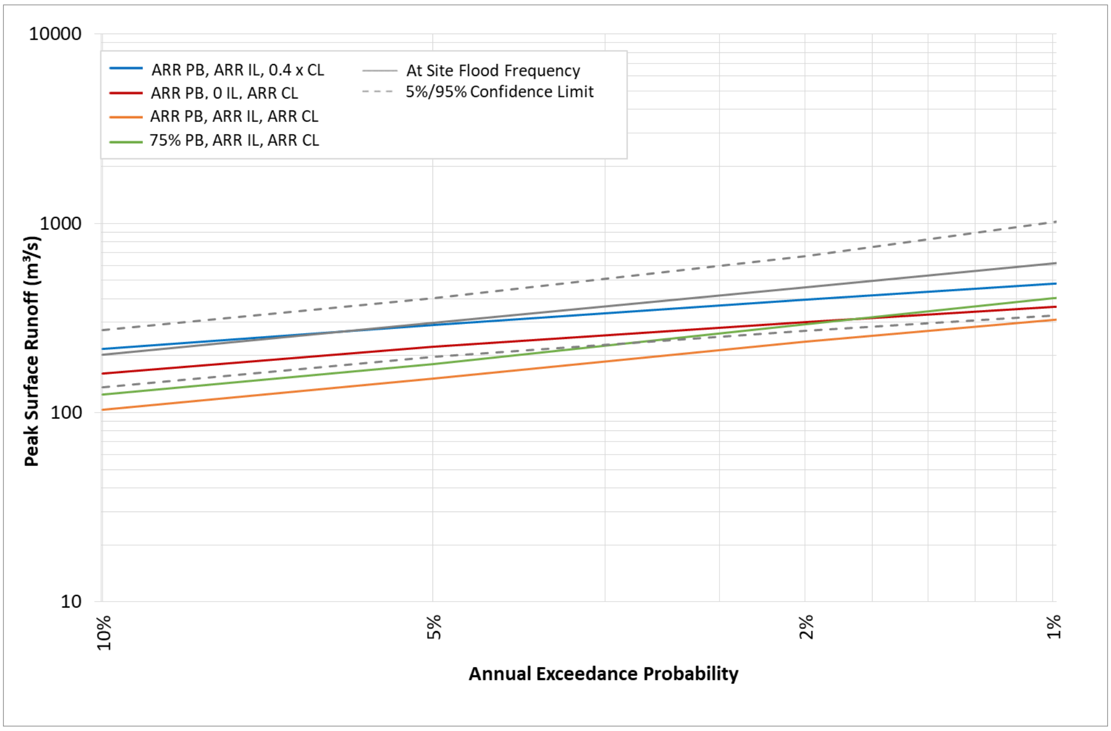


Figure E-9: Aberfeldy River at Beardmore (225213)

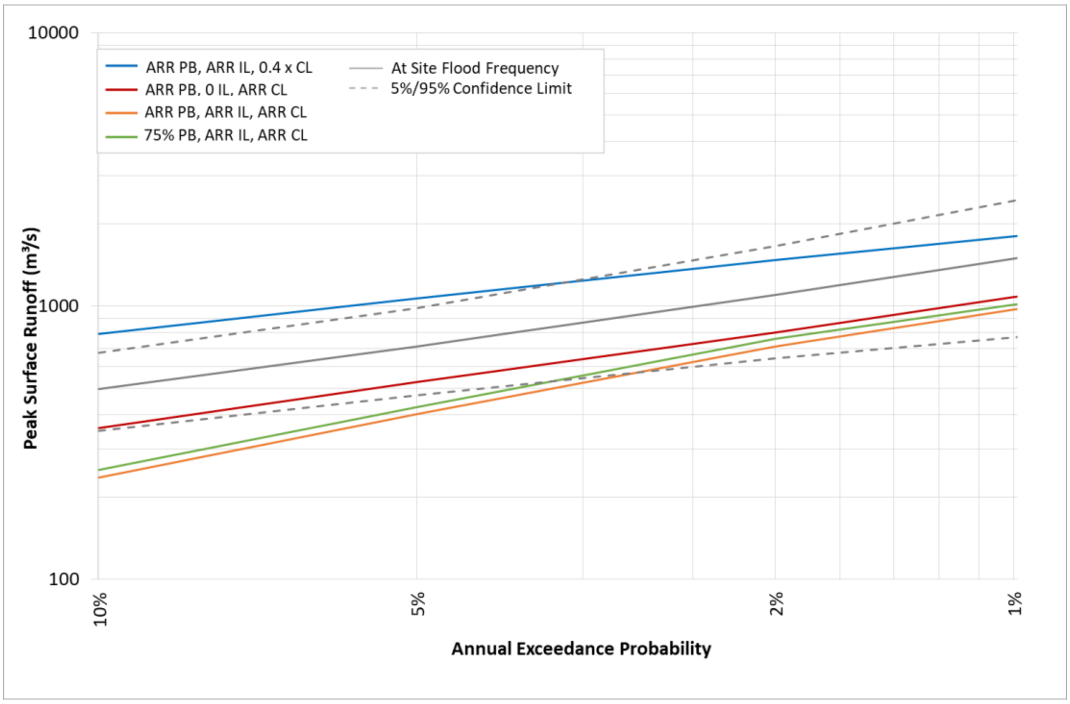
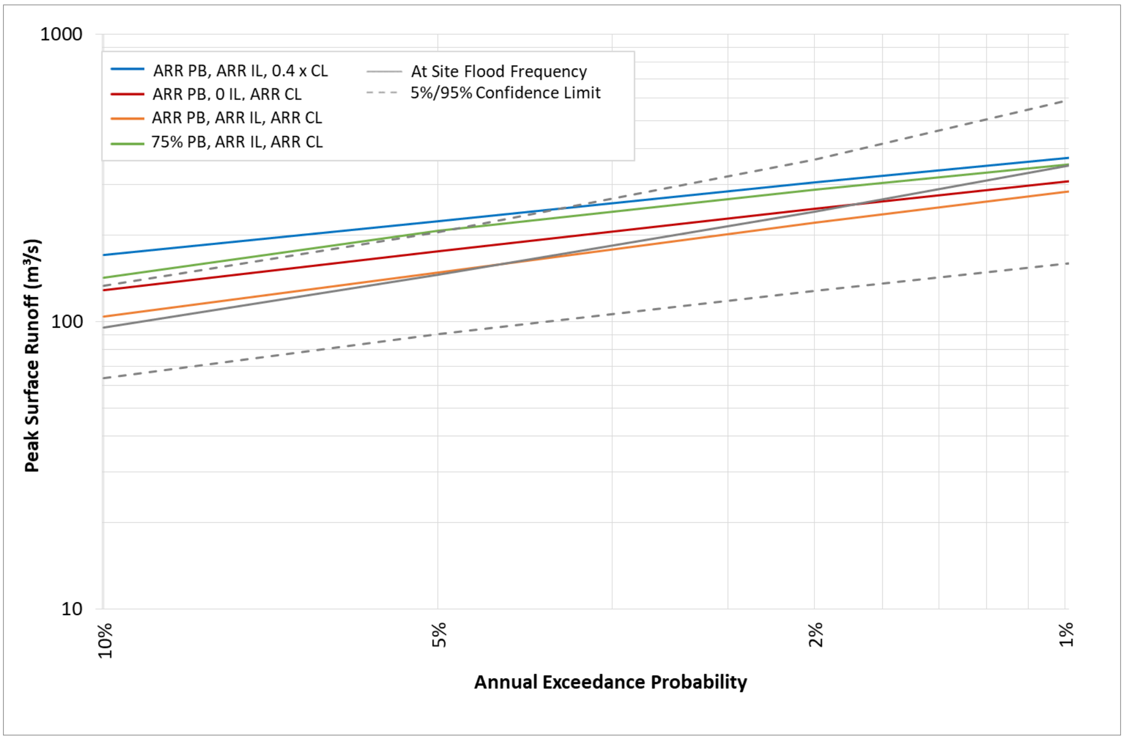
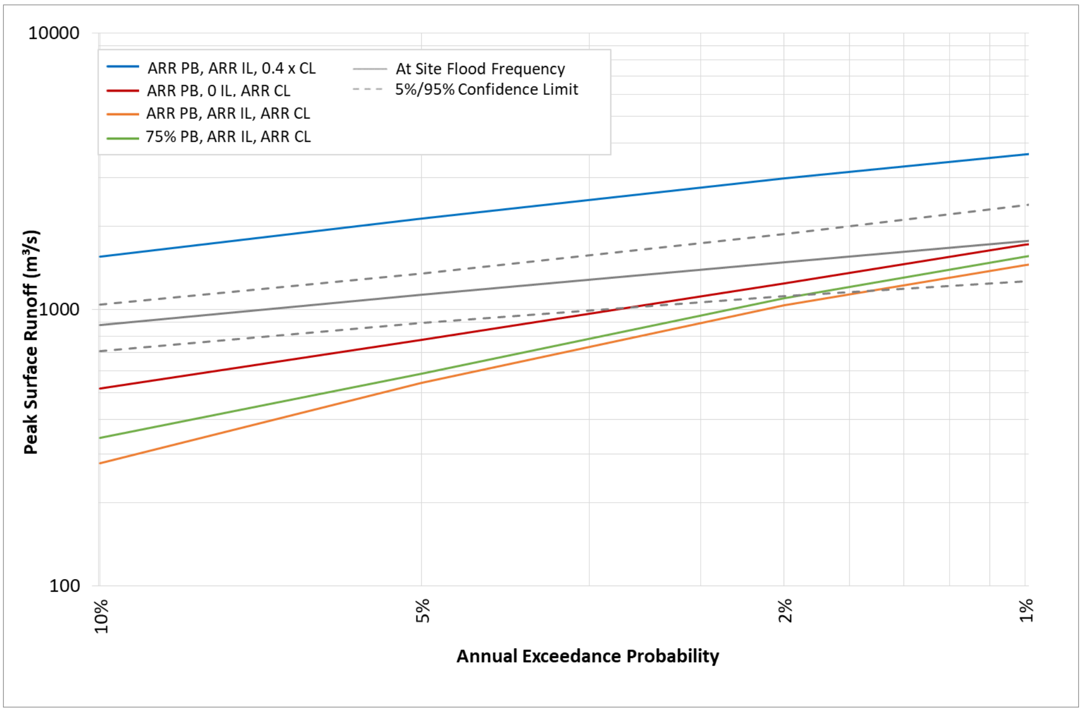


Figure E-10: Macalister River at Stringybark Creek (225221)



■ **Figure E-11: Traralgon Creek at Traralgon (226023)**



■ **Figure E-12: Mitchell River at Glenaladale (224203)**

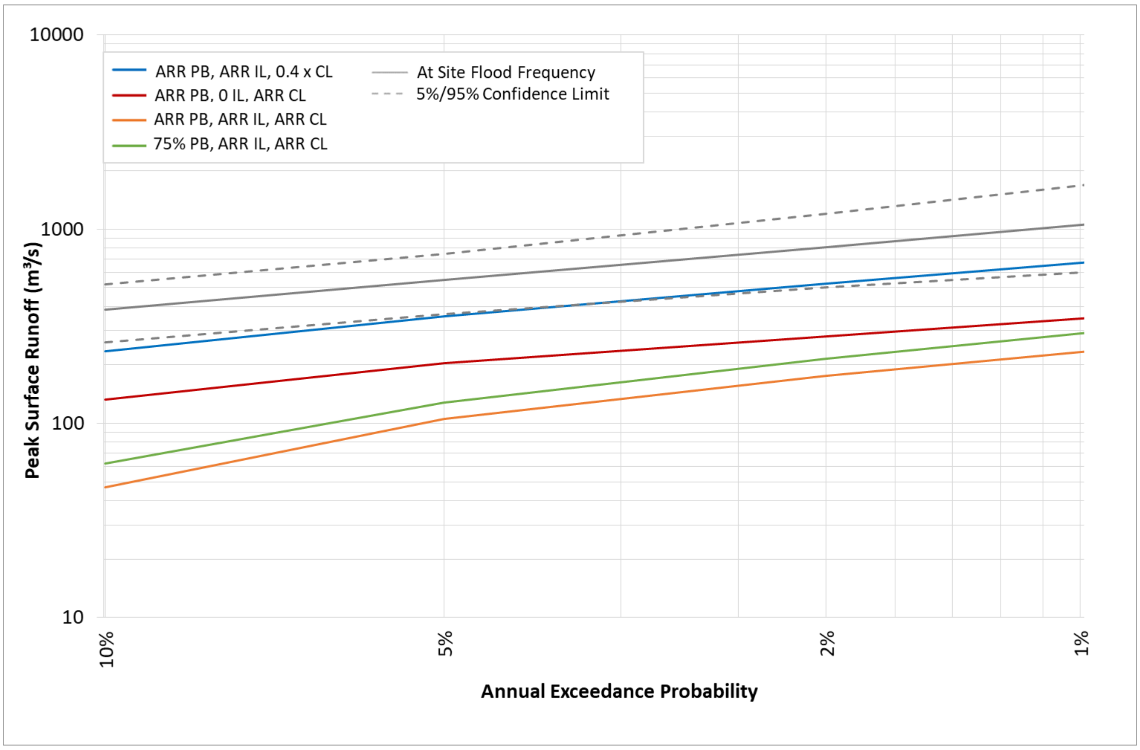


Figure E-13: Avoca River at Coonooer (408200)

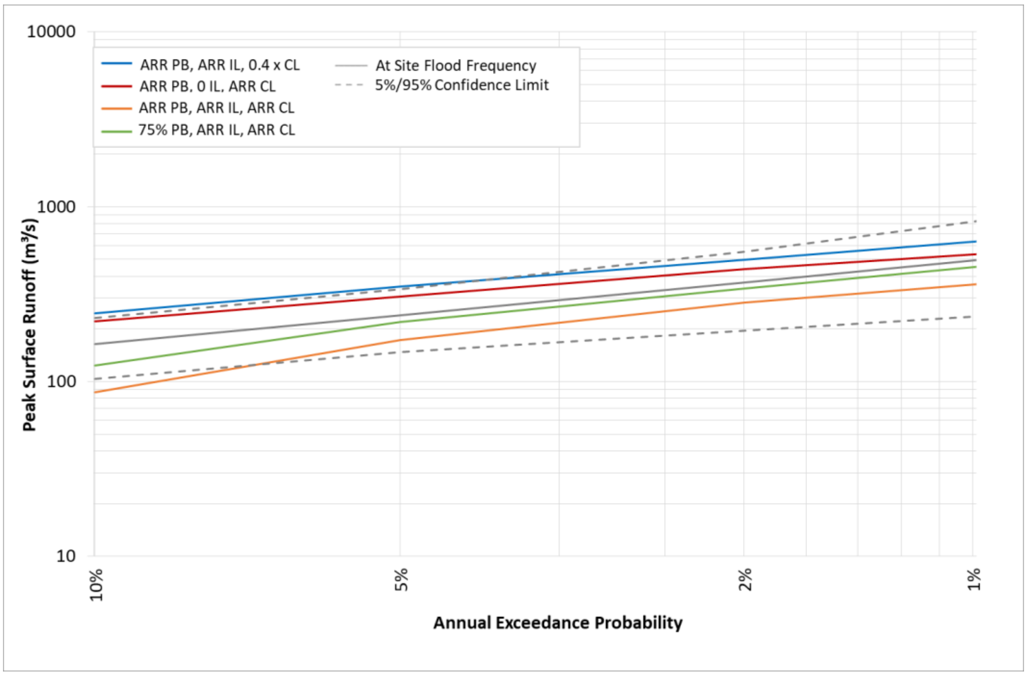


Figure E-14: Tullaroop Creek at Clunes (407222)

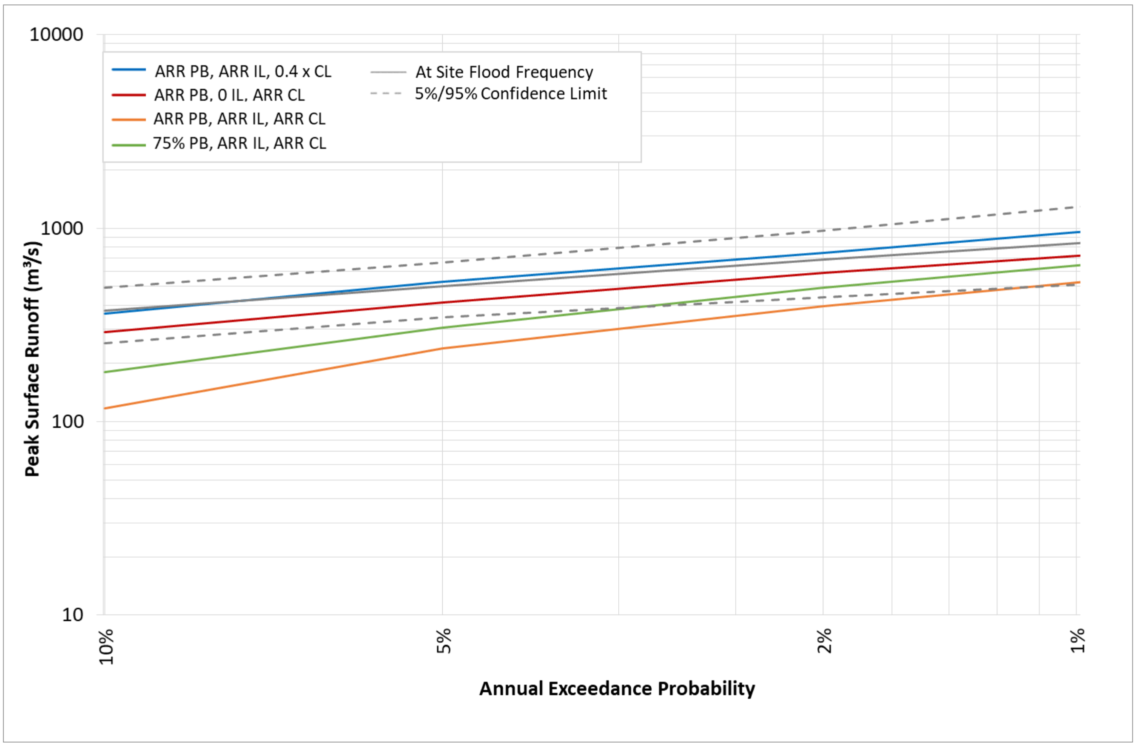


Figure E-15: Loddon River at Newstead (407215)

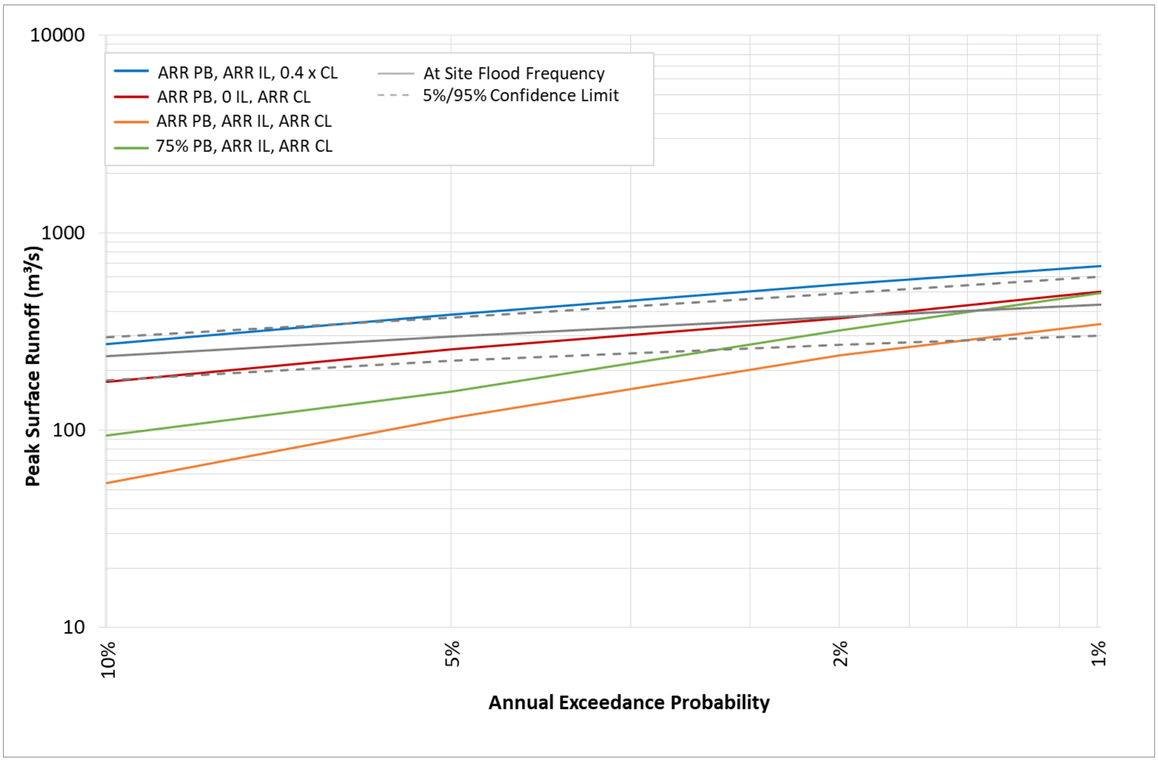
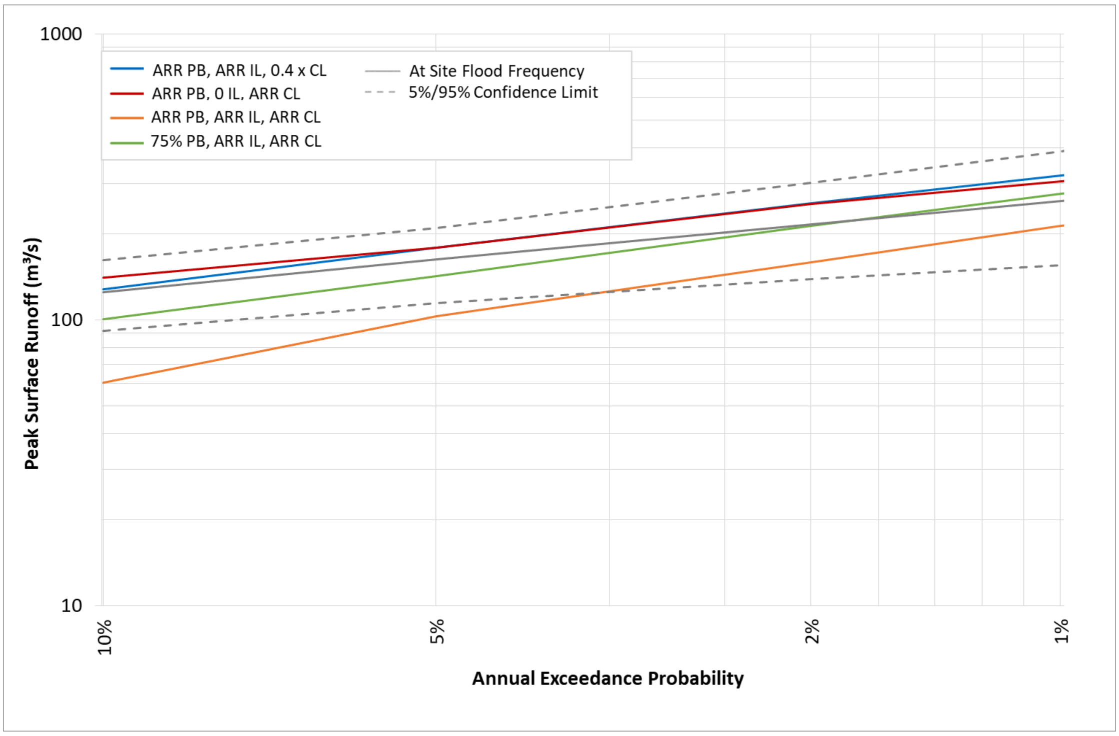
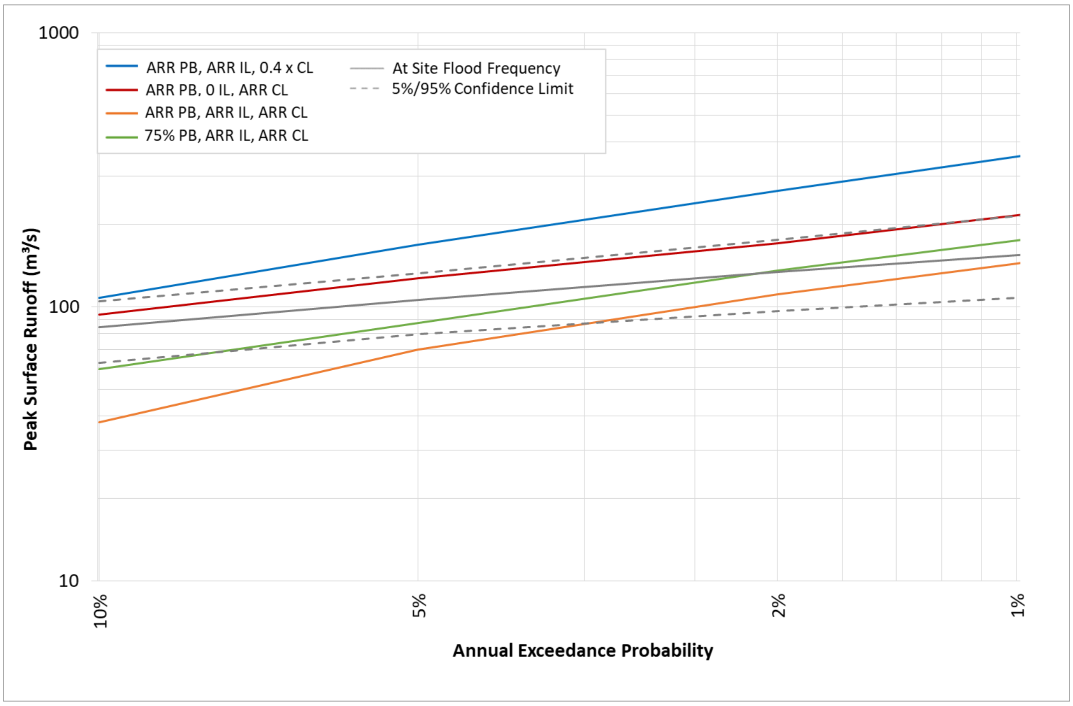


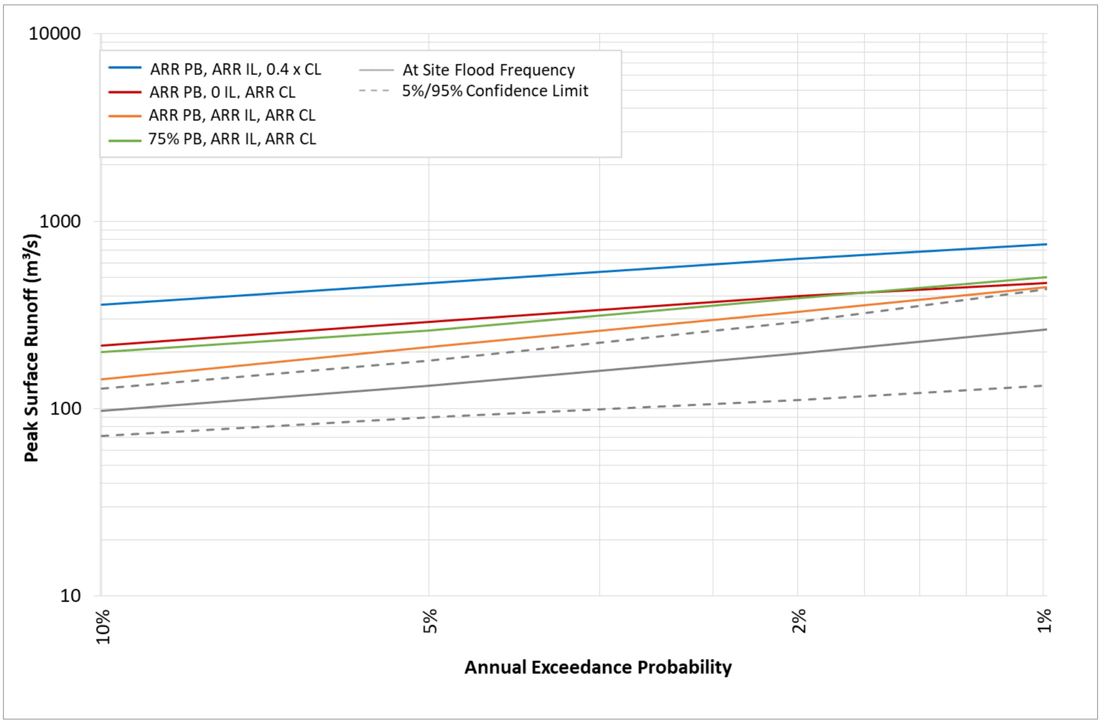
Figure E-16: Campaspe River at Redesdale (406213)



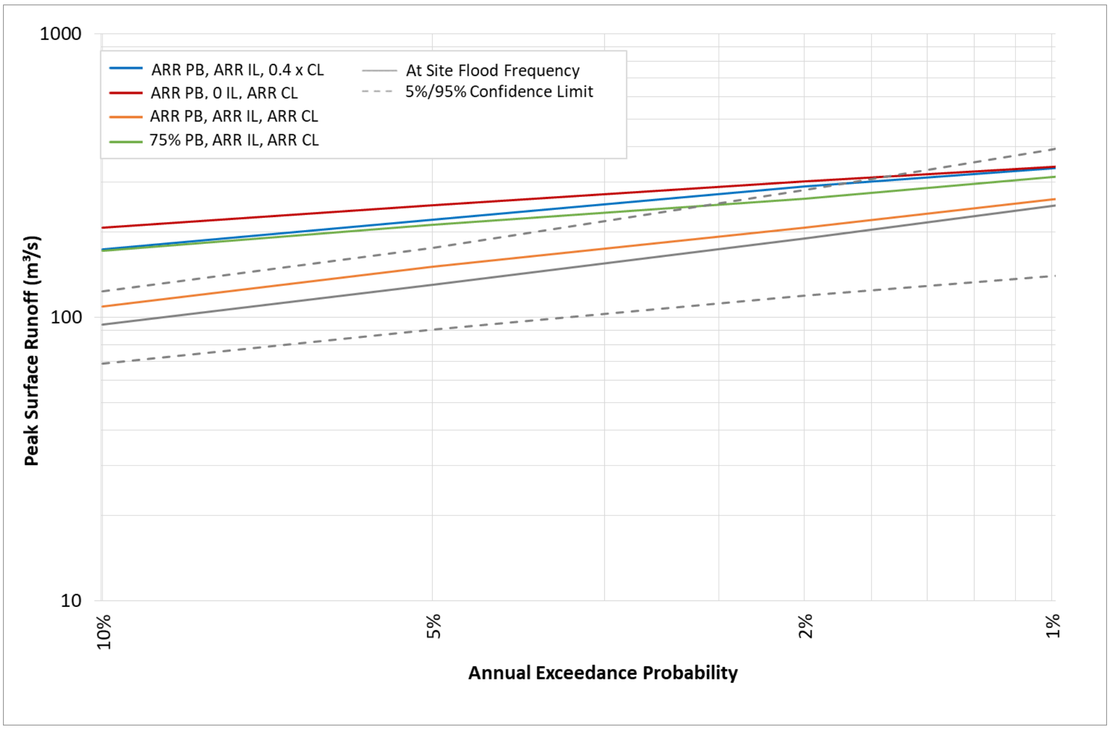
■ **Figure E-17: Major Creek at Graytown (405248)**



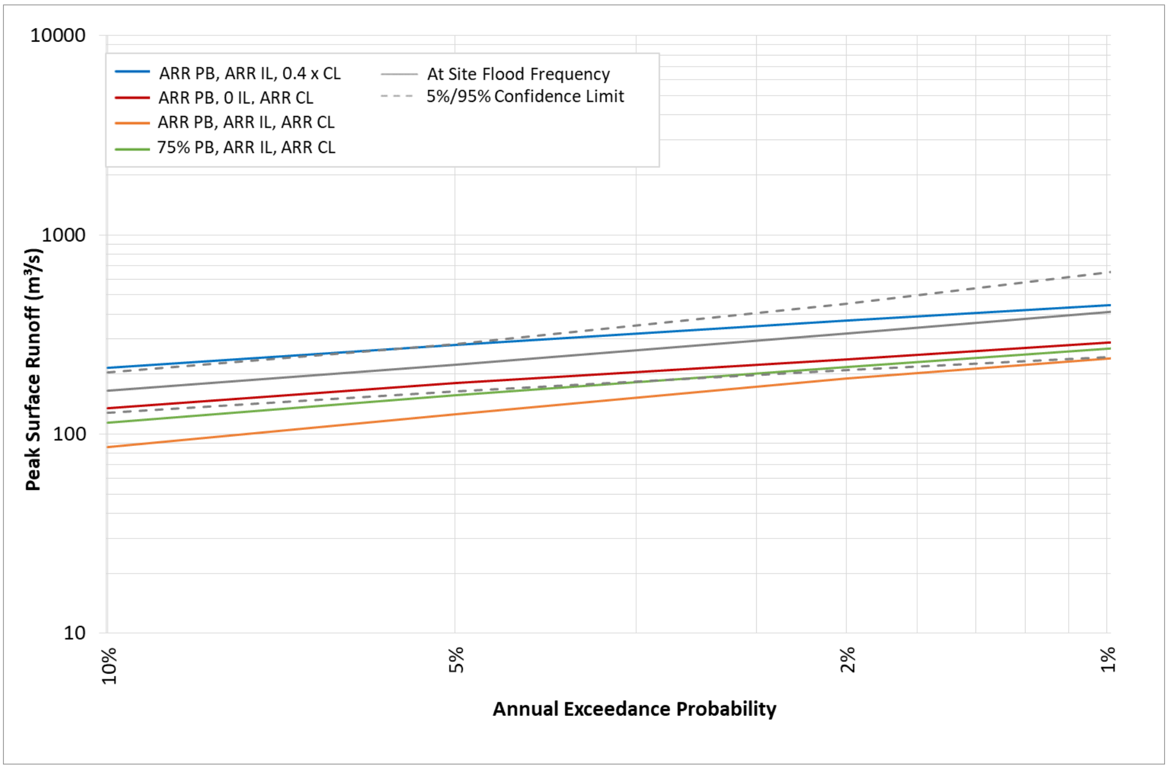
■ **Figure E-18: Pranjip Creek at Moorilim (405226)**



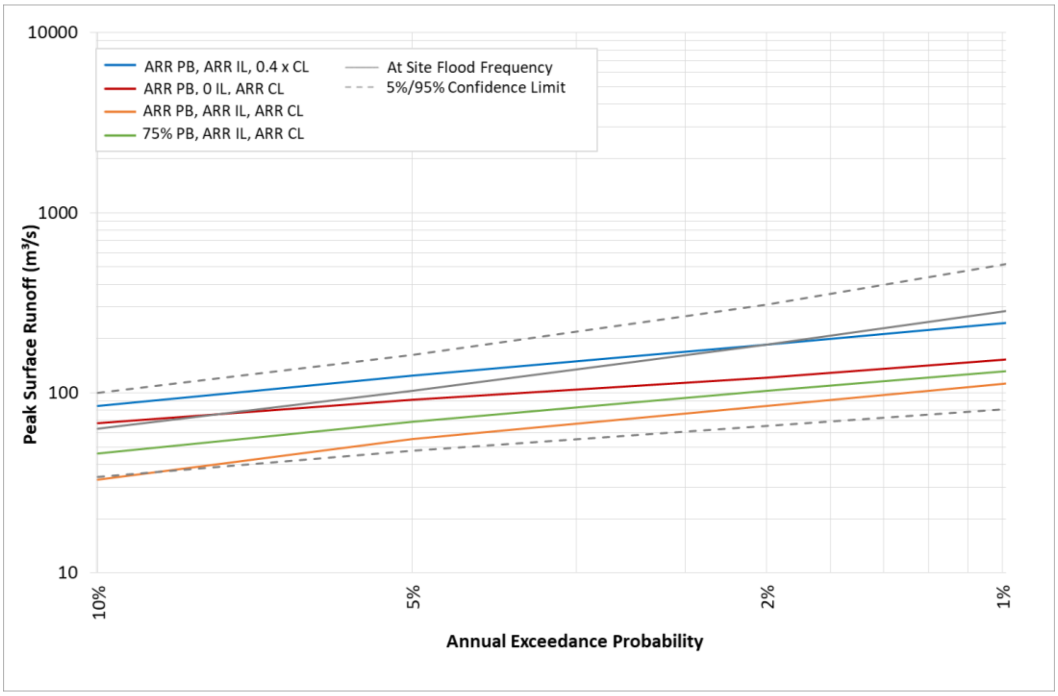
■ **Figure E-19: Acheron River at Taggerty (405209)**



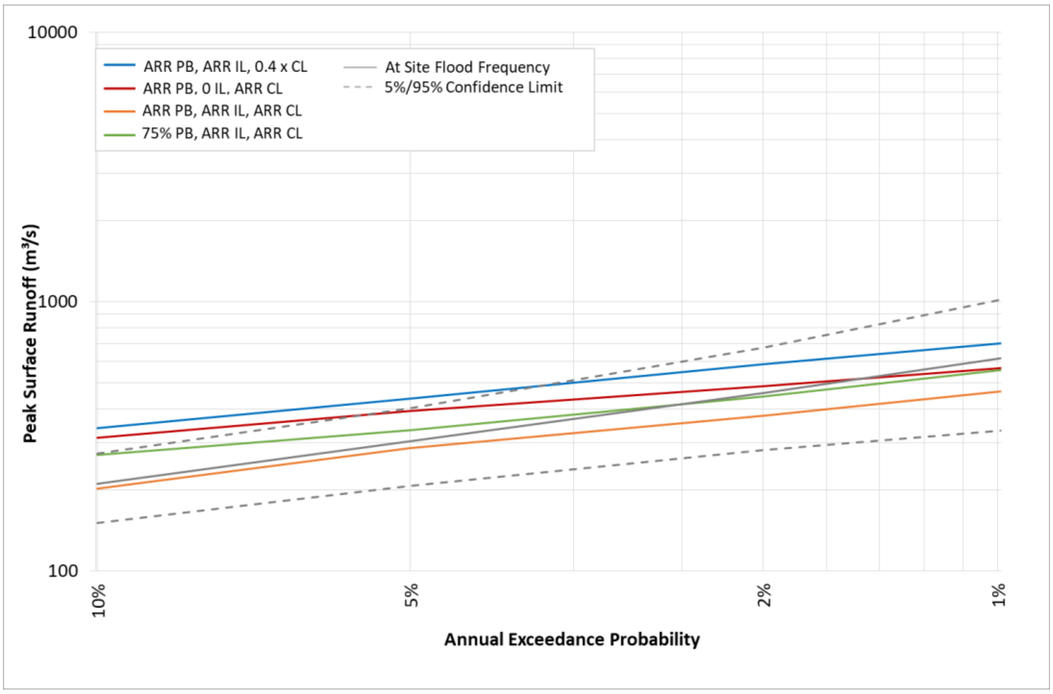
■ **Figure E-20: Ford Creek at Mansfield (405245)**



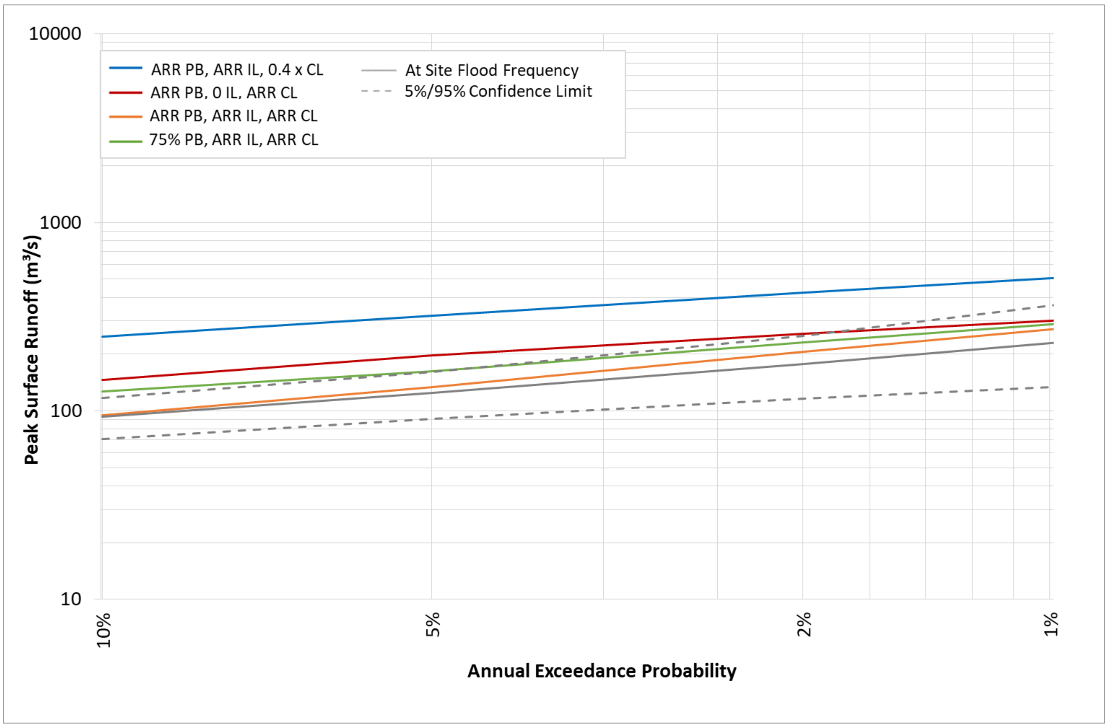
- **Figure E-21: Delatite River at Tonga Bridge (405214)**



- **Figure E-22: Boosey Creek at Tungamah (404204)**



- **Figure E-23: Holland Creek at Kelfeera (404207)**



- **Figure E-24: Buffalo River at Abbeyard (403222)**

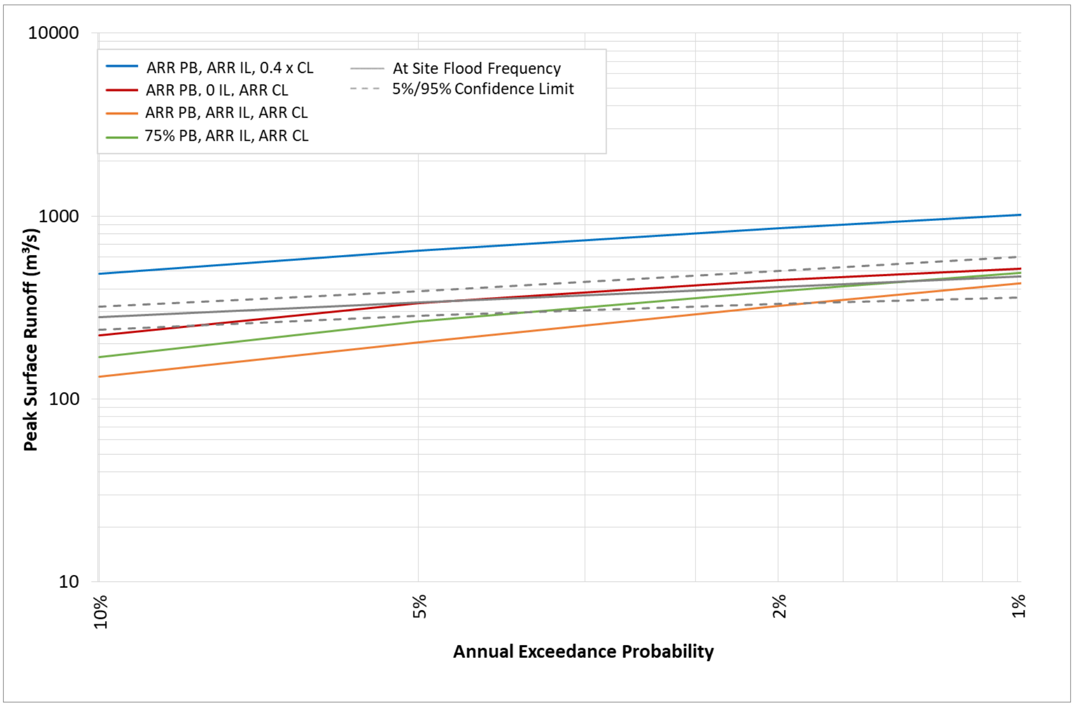


Figure E-25: Mitta Mitta River at Hinnomunjie (401203)