Australian Rainfall & Runoff

Revision Projects

PROJECT 2

SPATIAL PATTERNS OF RAINFALL

Collation and Review of Areal Reduction Factors from Applications of the CRC-Forge Method in Australia

FINAL REPORT

P2/S2/012

APRIL 2013

Australian Government

ENGINEERS AUSTRALIA
Water Engineering

AUSTRALIAN RAINFALL AND RUNOFF
REVISION PROJECT 2: COLLECTION AND REVIEW OF AREAL REDUCTION FACTORS

COLLATION AND REVIEW OF AREAL REDUCTION FACTORS FROM APPLICATIONS OF THE CRC-FORGE METHOD IN AUSTRALIA

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FOREWORD

AR&R Revision Process

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

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

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

However, many of the practices recommended in the 1987 edition of AR&R now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of ARR. A recent and significant development has been that the revision of ARR has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

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

Steering and Technical Committees have been established to assist the ARR Editorial Team in guiding the projects to achieve desired outcomes. Funding for Stages 1 and 2 of the ARR revision projects has been provided by the Federal Department of Climate Change and Energy Efficiency. Funding for Stages 2 and 3 of Project 1 (Development of Intensity-Frequency-

Duration information across Australia) has been provided by the Bureau of Meteorology.

Project 2 Spatial Patterns of Design Rainfall

Rainfall estimates from IFD relationships are applicable strictly only to a single point and not to a wider area such as a catchment. However, where the catchment area is small, the point IFD relationships is taken to be representative of the areal IFD relationship. For this purpose, a small catchment would be defined as being less than $4km^2$. For larger areas, it is unrealistic to assume that the same intensity rainfall will occur over the entire area and reductions in the rainfall intensity are made. Unfortunately, at present there is limited information available regarding values for the Areal Reduction Factor (ARF). Due to this, Canterford et al. (1987) recommended the use of areal reduction factors developed by the US National Weather Service (NOAA, 1980) for the Chicago region as being appropriate for all regions of Australia except for the inland regions where the recommendation is to use areal reduction factors developed for Arizona (NOAA, 1984). Hence the ARFs currently recommended for use in Australia were not defined from Australian data. Since that recommendation, Srikanthan (1995), Siriwardena and Weinmann, (1996) and Catchlove and Ball (2003) have investigated ARFs using Australian data for different regions of the country. These studies have highlighted the inappropriateness of American ARFs for Australian conditions.

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

AR&R REVISION PROJECTS

The 21 AR&R revision projects are listed below :

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

AR&R Technical Committee:

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PROJECT TEAM AND CONTRIBUTORS TO CRC-FORGE PROJECTS FOR AREAL REDUCTION FACTORS

This report was prepared by Erwin Weinmann and Phillip Jordan, Peter Hill and Chloe Wiesenfeld of Sinclair Knight Merz.

The report compiles the areal reduction factors (ARFs) from the extensive volume of work that was undertaken during the application of CRC-FORGE across each of the states and the ACT. The authors therefore gratefully acknowledge the work undertaken by the following people:

- Sri Srikanthan, who undertook the literature review of ARF methods for the CRC-FORGE project in Victoria;
- Lional Siriwardena, who was a researcher in the Victorian CRC-FORGE project;
- Nanda Nandakumar, who assisted with the development, testing and application of software for deriving areal reduction factors for the Victorian, South Australian, Western Australian, New South Wales and ACT projects;
- Simon Gamble, Fiona Ling, Crispin Smythe and Kirsten Adams, who undertook the Tasmanian application of CRC-FORGE;
- Gary Hargraves, who undertook the Queensland application of CRC-FORGE;
- Jacqui Durrant, who undertook the application of CRC-FORGE in Western Australia;
- Nanda Nadakumar and Kristen Sih, who undertook the application of CRC-FORGE in New South Wales and the Australian Capital Territory.

The authors also gratefully acknowledge the funding provided by the following organisations for the development and application of the CRC-FORGE method:

- The participant organisations in the Cooperative Research Centre for Catchment Hydrology; [1]
- Hydro Tasmania;
- SA Water;
- Cairns City Council;
- CS Energy;
- Queensland Department of Natural Resources;
- Gladstone Area Water Board;
- Gold Coast City Council;
- South East Queensland Water Board;
- Stanwell Corporation;
- Tarong Energy;
- Toowoomba City Council;
- Townsville / Thuringowa Water Board;

[1] The parties to the CRC for Catchment Hydrology were Brisbane City Council; Australian Government Bureau of Meteorology; CSIRO Land and Water; New South Wales Department of Infrastructure, Planning and Natural Resources; Victoria Department of Sustainability and Environment; Goulburn-Murray Water; Grampians Wimmera Mallee Water Authority; Griffith University; Melbourne Water; Monash University; Murray-Darling Basin Commission; Queensland Deparment of Natural Resources, Mines and Energy; Southern Rural Water and the University of Melbourne

- State Water (NSW);
- ACTEW Corporation;
- ACTEW AGL; and
- WA Water Corporation.

EXECUTIVE SUMMARY

Design rainfall information for flood estimation is generally made available to designers in the form of *point rainfall intensities* (e.g. the rainfall intensity-frequency-duration information given in "Australian Rainfall and Runoff", Institution of Engineers Australia, 1987/1998). However, most flood estimates are required for catchments of significant size and will thus require a design estimate of the *areal average rainfall intensity* over the catchment. The ratio between the design values of areal average rainfall and point rainfall, computed for the same duration and annual exceedance probability (AEP), is called the *areal reduction factor (ARF)*. It allows for the fact that larger catchments are less likely than smaller catchments to experience high intensity storms simultaneously over the whole of the catchment area.

This report provides a summary of ARF assessments around Australia that are recommended for current use in design practice. It also provides a list of recommendations for future research work to further reduce any potential uncertainty in design flood estimates introduced due to uncertainties in the ARF.

The ARF zones that have been defined by the application of the CRC-FORGE method in each state are shown in Figure ES- 1.

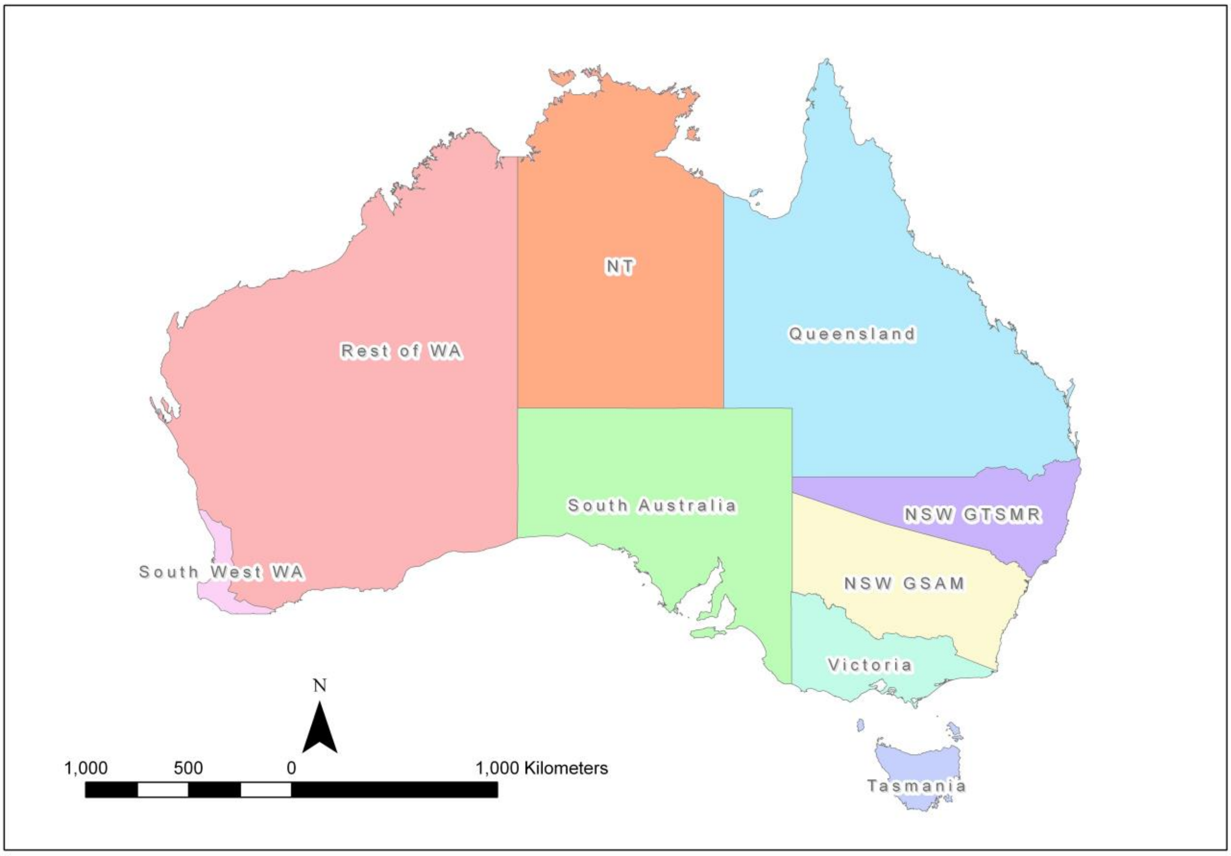

Figure ES- 1 ARF zones after completion of all the CRC-FORGE projects

Long duration areal reduction factor equations

Considerable progress has been made on the derivation of ARFs using Australian data since the 1987 edition of Australian Rainfall and Runoff . Projects undertaken in each of the Australian states and territories to produce the CRC-FORGE estimates of design rainfall also produced equations for ARFs that are applicable for long durations (18 to 120 hours) and for catchment areas between 1 and 10,000 km² and AEPs between 0.5 and 0.0005. These locally developed equations have been developed using large databases of daily rainfall data that have been appropriately quality controlled and using consistent applications of Bell's (1976) method. The equations for long durations developed using these CRC-FORGE studies are therefore more applicable to Australia then the equations recommended in Australian Rainfall and Runoff (1987).

It is recommended that the long duration equations derived as part of the CRC-FORGE studies discussed in this report and summarised in Section 4 are adopted for ARFs in Australia. The long duration areal reduction factor equations all follow the general form shown below in Equation 1.

The parameters in the formulae for each region are detailed in Table ES- 1.

$$\begin{aligned} Areal\ reduction\ factor \\ = Min\{1, [1 + a(Area^b + c\log_{10} Duration)Duration^d \\ + eArea^f Duration^g (0.3 + \log_{10} AEP)]\} \end{aligned}$$

Where

Area = Area of interest in km²

Duration = Storm duration in hours (between 18 and 120 hours)

AEP = Annual exceedance probability as a fraction between 0.5 (1 in 2) and 0.0005 (1 in 2000)

Equation 1

Table ES- 1 Parameters for long duration areal reduction factor equations (in the form of Equation 1) for each region

Region	**a**	**b**	**c**	**d**	**e**	**f**	**g**
Victoria	-0.4	0.14	-0.7	-0.48	0.0002	0.4	0.41
Tasmania	-0.105	0.216	-0.882	-0.343	0.0012	0.223	0.335
South Australia	-0.14	0.22	-1.09	-0.42	0.0001	0.35	0.5
Western Australia Annual	-0.13	0.21	-0.56	-0.45	0	-	-
Queensland	-0.2257	0.1685	-0.8306	-0.3994	0	-	-
New South Wales GSAM (including ACT)	-0.23	0.183	-0.91	-0.43	0.00048	0.38	0.21
New South Wales GTSMR	-0.19	0.2	-0.87	-0.412	0	-	-
Northern Territory	As interim measure, adopt Queensland parameters						

Western Australia was the only state where parameter sets for the ARF equation were derived for the winter and summer seasons, which were distinct from the parameters applicable for annual curves in Western Australia. The summer season for Western Australia was defined as the months of October to March inclusive. Seasonal ARF parameter sets for Western Australia are as shown in Table ES- 2.

Table ES- 2 Parameters for long duration areal reduction factor equations (in the form of Equation 1) for two seasons in two regions of Western Australia

Region	a	b	c	d	e	f	g
Western Australia Winter	-0.11	0.24	-0.3	-0.52	0.0004	0.32	0.38
Western Australia South West Summer	-0.11	0.25	-0.35	-0.48	-0.1408	0.01	-0.52
Rest of Western Australia Summer	-0.23	0.17	-0.57	-0.4	-0.0287	0.21	-0.41

Short duration areal reduction factor equations

Analysis of ARFs for shorter duration events (less than 18 hour duration) in Australia is considerably less extensive than for long duration events (18 to 120 hour duration). As an interim measure, equations for short duration events have been derived that produce consistency with the long duration ARF equations in each region and that assume the 1 hour duration ARF values derived in the United Kingdom Flood Studies report are also applicable to Australia (Natural Environmental Research Council, 1975). To ensure consistency of ARFs across all durations less than 18 hours for all areas, parameters of the interim short duration curves for some regions were re-derived as part of the current project. The re-derived interim curves resulted in relatively minor differences to the interim curves that were produced by previous authors. While further research work to establish ARFs derived from Australian data would be desirable for short duration events, it is recommended that the adjusted interim ARF equations are adopted for use in Australia until this future research produces an alternative recommended equation.

The short duration areal reduction factor equations all follow the general form shown below in Equation 2. The parameters in the formulae for each region are detailed in Table ES- 3.

$$Areal\ reduction\ factor = Min\left\{1, \left[1 + a\left(Area^{b} + c\right) + d(Area^{e})(f - \log_{10} Duration)\right]\right\}$$

Where

Area = Area of interest in km²

Duration = Storm duration in hours (between 1 and 18 hours)

Equation 2

Table ES- 3 Parameters for short duration areal reduction factor equations (in the form of Equation 2) for each region

Region	a	b	c	d	e	f
Victoria	-0.1	0.14	-0.879	-0.029	0.233	1.255
Tasmania	-0.0342	0.222	-1.094	-0.0291	0.302	1.29
South Australia	-0.015	0.014	-6.12	-0.05	0.18	2.48
Western Australia	-0.0518	0.257	-0.553	-0.0231	0.333	0.63
Queensland	-0.0539	0.205	-0.925	-0.0246	0.313	1.16
New South Wales – GTSM–R	-0.0449	0.207	-1.032	-0.0258	0.299	1.37
New South Wales – GSAM (including ACT)	-0.0439	0.23	-0.923	-0.0255	0.309	1.17
Northern Territory	As interim measure, adopt Queensland parameters					

TABLE OF CONTENTS

1. Introduction

1.1. Background

Design rainfall information for flood estimation is generally made available to designers in the form of *point rainfall intensities* (e.g. the rainfall intensity-frequency-duration information given in "Australian Rainfall and Runoff", Institution of Engineers Australia, 1987/1998). However, most flood estimates are required for catchments of significant size and will thus require a design estimate of the *areal average rainfall intensity* over the catchment. The ratio between the design values of areal average rainfall and point rainfall, computed for the same duration and annual exceedance probability (AEP), is called the *areal reduction factor (ARF)*. It allows for the fact that larger catchments are less likely than smaller catchments to experience high intensity storms simultaneously over the whole of the catchment area.

Due to a lack of adequate research carried out in Australia to derive ARF for use in the different parts of the country, "Australian Rainfall and Runoff" (ARR87, IEAust, 1987) recommended the set of curves derived from a study in the Chicago area for all Australian zones except for the dry inland area of Zone 5 (Figures 2.6 and 3.2 in ARR87). These ARF values apply to design rainfalls for any average recurrence interval (ARI) up to 100 years. The ARFs obtained from a study in the Arizona area, a semi-arid part in the United States, were recommended for use in Zone 5 (Figure 2.7 in ARR87).

There has since been a concern in some sections of the Australian hydrological community that the results from the United States may not be appropriate for the Australian conditions. This concern was confirmed by a number of studies (Nittim, 1989; Avery, 1991; Porter and Ladson, 1993; Masters, 1993; Masters and Irish, 1994; Meynink and Brady, 1993) in which the authors found that the values from ARR87 were generally larger than those from their own study. Moreover, studies in the United Kingdom (Bell, 1976; Stewart, 1989) have conclusively shown that ARFs for that region are dependent on the annual exceedance probability (AEP) of the rainfall.

The above established the development of ARFs appropriate to Australia as a high priority research area in flood estimation.

1.2. The CRC-FORGE Projects

The Cooperative Research Centre for Catchment Hydrology (CRCCH) undertook a research project in the mid-to-late-1990's investigating design rainfall intensities for very large and extreme rainfall events for catchments in Victoria, which developed a method known as the Cooperative Research Centre – Focussed Rainfall Growth Estimation Method or CRC-FORGE. The process of compiling, quality controlling and producing consistent data sets of daily rainfall across a wide area (Victoria) provided the opportunity to advance the development of Victorian-specific ARFs for longer duration (18 to 120 hour) rainfall events.

Subsequent projects applying the CRC-FORGE method to design rainfall estimation were undertaken over the following decade in the other Australian states and the Australian Captital Territory. These projects also compiled rainfall data sets, and separate ARF equations were derived in each of these projects for each of the individual regions, using virtually identical techniques for deriving long duration ARF to those used in the Victorian CRC-FORGE project. No CRC-FORGE project has yet been undertaken for the Northern Territory nor in Australia's off-shore territories and as a result no ARF equations have been specifically derived for these territories.

A review report by Srikanthan (1995) constituted the first stage of the Victorian CRC-FORGE project for the derivation of ARFs. Based on his review of the existing methods available for derivation of ARF, Srikanthan recommended the use of Bell's (1976) method for deriving ARF for those regions *where sufficient daily rainfall data is available*. Bell's method is an empirical approach, which allows the derivation of ARFs as a function of AEP.

The objective of the CRC-FORGE projects was to appropriately modify Bell's (1976) method to suit Australian rainfall data, and then derive ARF values for different regions of Australia, making use of the large daily rainfall database. The study method was applied on a trial basis and further developed using Victorian data (Siriwardena and Weinmann, 1996a,b), and then applied separately to the data sets for other states. With appropriate extrapolations, the study method allows derivation of ARF values for rainfall durations from 18 to 120 hours, areas up to 10,000 km^2 and AEP ranging from 1 in 2 to about 1 in 1000. The results were then presented in a suitable format useful to the practitioner, such as a set of curves or mathematical relationships expressing the variation of ARF values with duration, area and AEPs.

In principle, Bell's method could also be applied for the derivation of ARFs for rainfall durations less than 18 hours but the development of equations applicable across a wide region requires compilation, quality control and analysis of pluviograph data from a large number of stations across each region and/or similar analysis of gauge-calibrated radar rainfall data, which would require considerable effort that has not been undertaken to date.

To ensure consistency with the new ARF values for longer durations for Victoria, Siriwardena and Weinmann (1996 a) derived *interim ARF curves* for durations less than 18 hours, based on a comparison of the results of Australian studies with results from the analysis of UK rainfall data. Interim ARF curves were subsequently derived for each of the other regions (except for Tasmania, which adopted the Victorian interim short duration ARF curves), using a similar process to Siriwardena and Weinmann (1996a). These interim short duration equations were derived either at the same time as the derivation of the long duration ARFs in each region (with the CRC-FORGE study in each region – for SA, NSW and ACT), or subsequently by a different author (Qld and WA). Further work was undertaken during this current project to re-derive ARFs for Qld, WA, NSW and ACT (see Appendix A), resulting in relatively minor changes to the interim short duration equations in these states.

1.3. Australian Rainfall and Runoff 1987

The recommendation for areal reduction curves in ARR can be found in Book Two in Section 1.7 (IEAust, 1987). There are two sets of curves recommended for use, based on the temporal pattern zone (Figure 1-1) of the location of interest. The curves in Figure 1-2 were recommended for use for all of Australia, except for Zone 5 in Figure 1-1. For Zone 5 in Figure 1-1, the curves in Figure 1-3 were recommended. Given the paucity of studies in Australia at the time, these curves were sourced from the United States National Weather Service (1957) and were based on studies completed in Chicago for Figure 1-2 and Arizona for Figure 1-3.

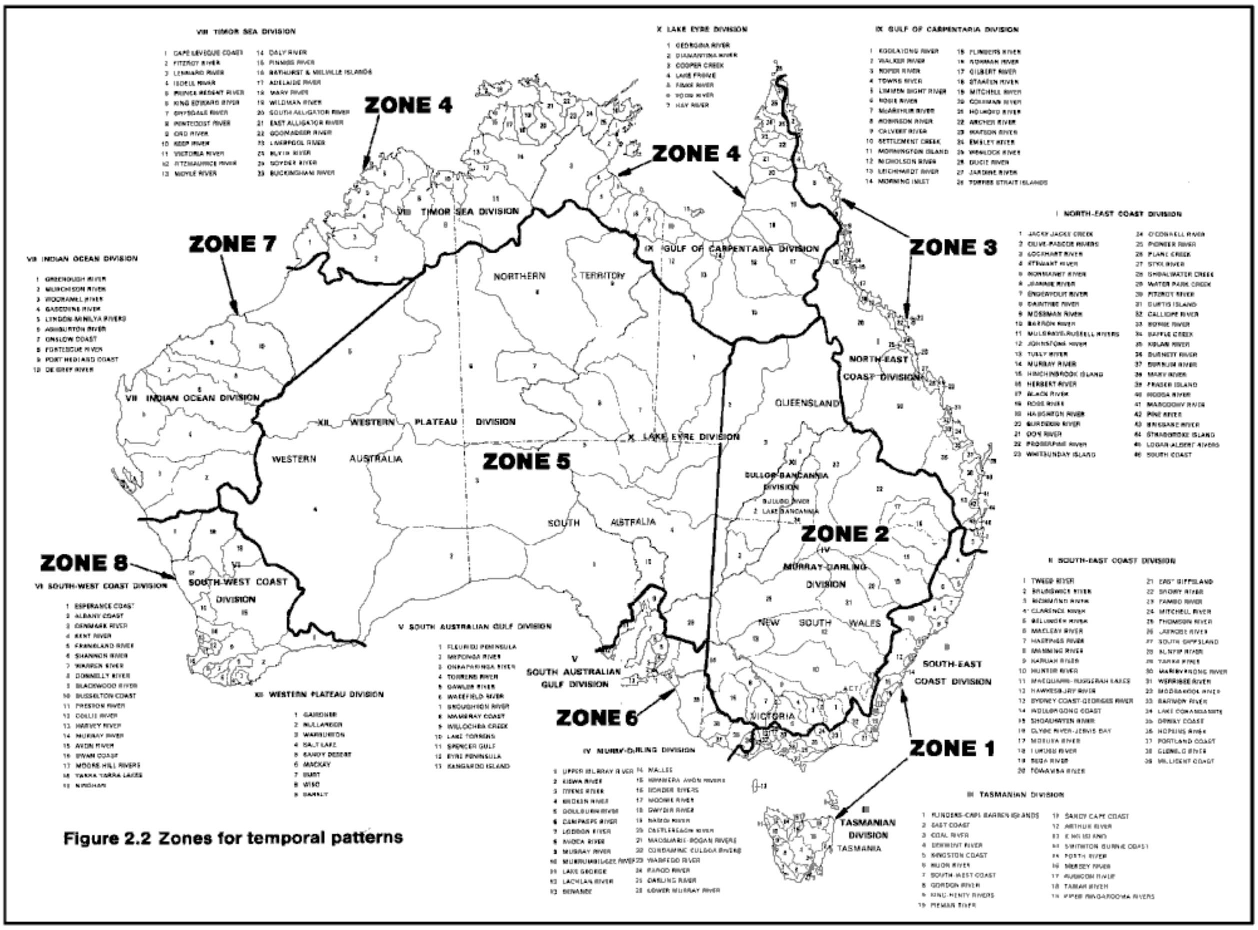

Figure 1-1 Zones for temporal patterns (Source: IEAust, 1987, *Australian Rainfall and Runoff 1987*, Figure 2.2)

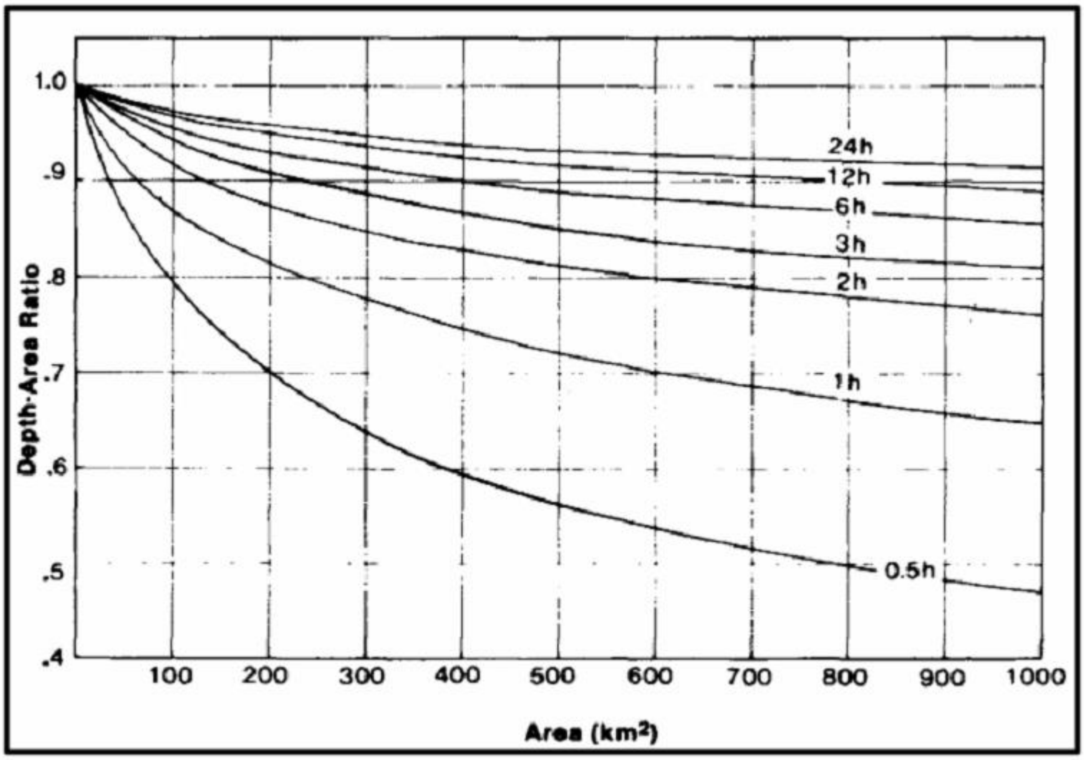

Figure 1-2 Depth-area Rations for use in Asutralia (Except for Zone 5 of Figure 1-1) (Source: From US NOAA Tech Report, NWS 24, 1980, in IEAust, 1987, *Australian Rainfall and Runoff 1987*, Figure 1.6)

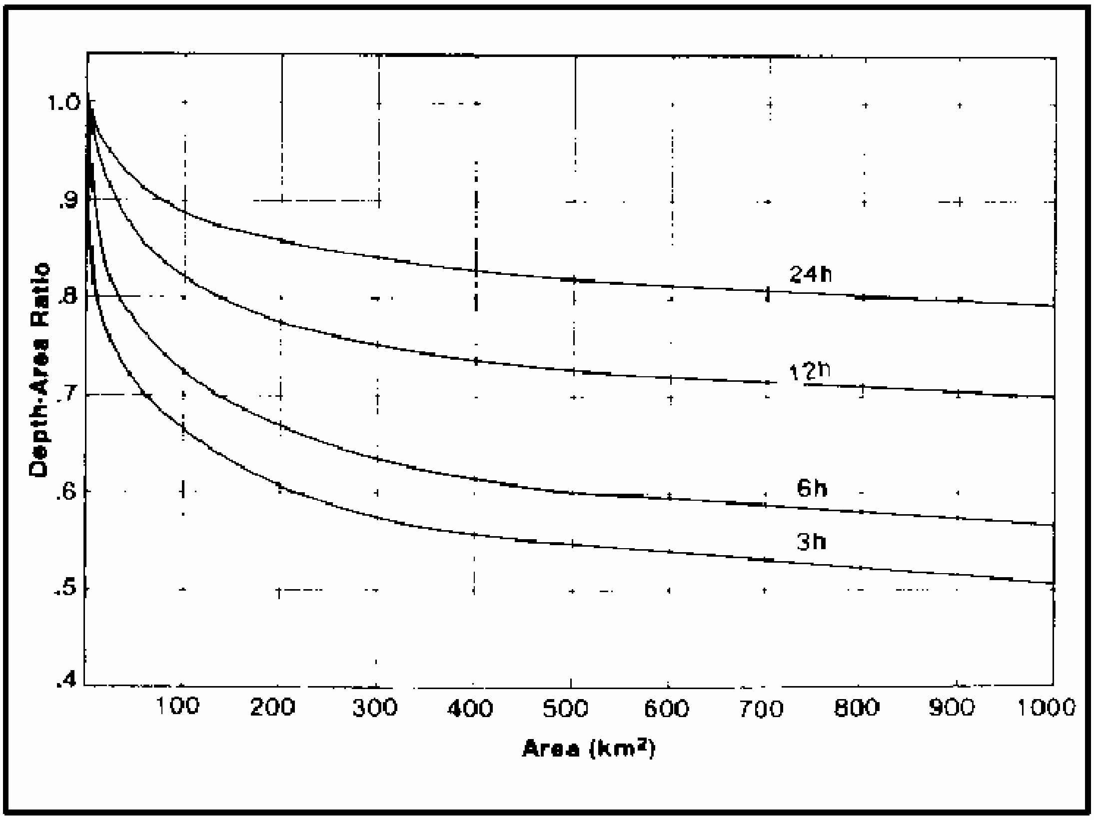

Figure 1-3 Depth-area Rations for use in inland Australia (Zone 5 of Figure 1-1) (Source: From US NOAA Tech Report, NWS 24, 1980, in IEAust, 1987, *Australian Rainfall and Runoff 1987*, Figure 1.7)

1.4. Purpose and scope of this report

While the development and application of the CRCCH method for deriving ARF values has been described in detail in various reports, this report has been commissioned to collate a summary of all the available analyses for Australia. For more detail on the analysis from specific states, the reader is referred to the relevant references.

As the report is based on CRRCH research undertaken in the mid to late 1990s, it does not cover more recent developments of ARF estimation methodology and applications from the international literature.

2. Previous work on deriving areal reduction factors

2.1. Methods for deriving areal reduction factors

Two types of ARF have been identified in the literature: ie. *storm-centered* and *fixed-area* ARF. The fixed-area type is the one that is relevant to estimating probability-based design rainfalls for catchments and is widely used in design practice. The methods available for deriving fixed-area ARF have been classified into three categories, namely analytical, empirical and analytical-empirical methods (Srikanthan, 1995).

In analytical methods, a mathematical model is fitted to characterise the space-time variation of rainfall with simplifying assumptions. The ARF is then derived analytically from the properties of the fitted model. The methods developed by Roche (1963), Rodriguez-Iturbe and Mejia (1974), Meynink and Brady (1993), Sivapalan and Blöschl (1998) and the statistical derivation of ARF (Omolayo, 1989) fall under this category. In all these methods, it is assumed that the rainfall process is stationary and isotropic.

In empirical methods, recorded rainfall depths at a number of stations within a “catchment” are used to derive the ARF empirically. The US Weather Bureau method (1957), the UK Flood Studies Report method (NERC, 1975) and Bell’s (1976) method fall under this category. The first two methods derive a single value of ARF for a given area and duration for all AEP, while Bell’s method derives the ARF as a function of AEP.

The Myers and Zehr (1980) method, was classified as an analytical-empirical method. It involves derivation of various statistical characteristics of annual maximum rain storms at pairs of stations, and the analytical processing of these statistics into ARF estimates. The ARF recommended in “Australian Rainfall and Runoff” (Fig. 2.6 in IEAust, 1987) for use over most of Australia are based on the application of this method with rainfall data from the Chicago area in the USA.

Instead of using gauged rainfall data, recorded radar rainfall fields and model-simulated rainfall fields have also be used to derive ARF (Seed at al., 1999).

2.2. Empirical methods using a probabilistic approach

Bell (1976) introduced the probabilistic interpretation of the ARF in terms of frequency curves of point rainfalls and areal rainfalls, as shown in Figure 1. With this interpretation, the ARF are estimated by taking the ratio of the areal and average point rainfall frequency estimates at the desired AEP. Using data for United Kingdom, Bell used a weighting procedure to calculate daily <u>areal</u> rainfall values over the period of record. These were ranked to obtain the 20 independent highest values for each sample area. The partial series of areal rainfalls was then fitted to an exponential distribution with parameters estimated by the method of maximum likelihood. For the <u>point</u> rainfall frequency curves, the 20 highest daily rainfalls for each station were first obtained. For each rank, the weighted average point rainfall value over the sample area was then calculated, and the ranked average values fitted to an exponential distribution. Finally, the required values of the ARF for AEP of 1 in 2, 5, 10 and 20 were calculated directly from the corresponding areal and average point rainfall estimates.

Bell (1976) concluded that there was a statistically significant trend towards lower ARF with lower AEP for both 24-hour and shorter duration rainfalls. The differences were of the order of 2 to 5% between the AEP of 1 in 2 and 1 in 20 for areas of 1000 km^2 and a duration of 24 hours.

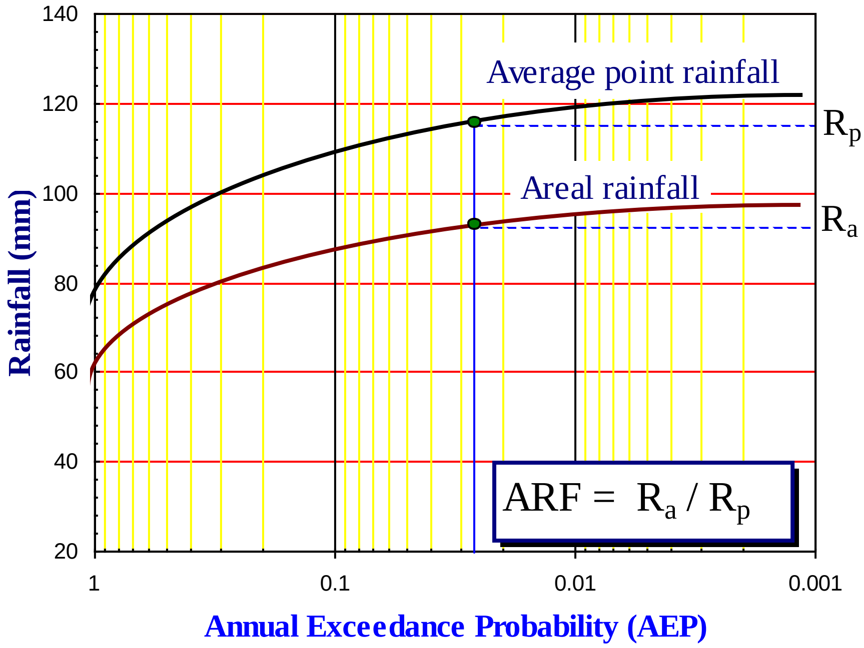

Figure 2-1 Probabilistic interpretation of areal reduction factors

Stewart (1989) derived ARF using a modified version of Bell's (1976) method. The procedure involved fitting a Generalised Extreme Value (GEV) distribution, by the method of Probability Weighted Moments, to derive areal and point rainfall growth curves representative of the whole region. Stewart (1989), using daily rainfall data for North-west England, confirmed the decrease in ARF with decreasing AEP.

2.3. Australian studies to derive areal reduction factors

In recent times, a number of studies have been carried out in Australia to derive ARF, but mainly for individual catchments within the south-eastern coastal region (Zone I as shown on Figure 1-1). In general, the study methods produce fixed-area ARF based either on empirical or analytical methods. A number of researchers (Nittim, 1989; Avery, 1991; Porter and Ladson, 1993) have used variations of Bell's method with point rainfall values estimated from the IFD curves given in ARR87. They used either a Log-normal or Log-Pearson III distribution to fit the annual series of areal rainfall. However, since IFD curves have been smoothed for spatial consistency, while the spatial rainfall estimates are unsmoothed, the resulting ARF values might not be consistent. Moreover, conversion of rainfall amounts from 'restricted' (e.g. daily) to 'unrestricted' (e.g. 24 h) intervals could introduce a potential error.

Some of the analytical methods used to derive ARF for different parts of Australia are based on the methods of Rodriguez-Iturbe and Mejia (1974) (Masters, 1993; Omolayo, 1993) or Myers and Zehr (1980) (Masters, 1993). Omolayo (1995) adopted a partial series model to evaluate ARF. Omalayo (1999) made a quantitative evaluation of sampling errors for ARF derived for Australian capital cities.

The general consensus of the above studies supports the qualitative conclusion that the ARF values given in Figure 2.6 of the ARR87 are conservative (Nittim, 1989; Avery, 1991; Porter and Ladson, 1993; Masters, 1993; Masters and Irish, 1994). However, these studies were confined to the capital cities and other relatively small areas within the south-eastern coastal region. The small databases used in the above studies preclude any firm quantitative conclusions on the appropriateness of the derived ARF values or their dependence on AEP.

3. Method adopted in areal reduction factor derivations undertaken with CRC-FORGE projects

3.1. Basis of method

Virtually identical methods were undertaken to derive long duration (18 to 120 hour) ARF curves in all of the CRC-FORGE studies undertaken in Australia. In all of the CRC-FORGE projects, the method used belonged to the group of empirical methods, where ARF values were computed directly from the analysis of rainfall data available for the catchment of interest. These empirical methods require few a priori assumptions but depend on the availability of extensive rainfall data sets with good spatial coverage. For the case of *daily rainfall data*, this requirement was generally satisfied for most regions in Australia.

The adopted method was a modification of Bell's (1976) method, thus allowing the determination of ARF that potentially can vary with AEP. For each selected catchment, frequency curves were fitted to the annual maximum values of average point rainfalls and areal rainfalls. For a given AEP, the ratio of the areal rainfall estimate to the point rainfall estimate represents the ARF. Regional design ARF values can be estimated from the analysis of a large number of actual or hypothetical catchments within a homogeneous region. Details of the methodology are given in Siriwardena and Weinmann (1996a, b).

3.2. Data requirements and catchment selection

Successful application of the method in any particular region depends on the availability of daily rainfall data in terms of network density, and length, completeness and accuracy of records. A minimum record length of 20 years was generally adopted, but longer record lengths are desirable to allow confident estimation of ARF for lower AEP. As the analysis is mainly based on annual maximum events, the accuracy of large rainfall observations is particularly important. The procedure does not require missing data to be filled-in, but the disaggregation of accumulated data into daily rainfalls is desirable, particularly for large events.

The analysis was based on hypothetical catchments and circular 'catchments' were adopted for computational convenience in all of the CRC-FORGE projects. In the selection of catchments, some constraints were imposed to safeguard the accuracy of the results, with circular "catchments" only defined where sufficient density of rainfall gauges existed. The minimum number of stations required was three for catchment areas up to 500km², with one additional station for every 500km² thereafter, so that (for example) a potential 2000km² circular catchment was not used unless it contained 6 gauges. Some of the circular catchments were also discarded if the spatial distribution of gauges across the catchment was not sufficiently uniform, so that one gauge would dominate the estimation of the mean areal rainfall for across the circle. If the proportion of a catchment closest to one of the gauges was greater than a specified threshold (Table 3-1), the circular catchment was discarded.

For each catchment size, some physical overlapping of catchment areas was permitted. In some cases, two catchments centres were quite close together, but provided that less than a third of the gauges were shared in common between the two catchments, the overlapping was permitted.

Length of record was also a consideration in the data requirements for each catchment. A minimum of 30 concurrent years was required. For example, for a 2000km² catchment, a 30 year period was needed during which at least 6 gauges were recording for each day throughout the recorded data after the data had been automatically infilled and disaggregated. This requirement increased for the 1 in 100 AEP, with 50 years of concurrent data required for a valid estimate of ARFs for the 1 in 100 AEP.

As an example, Figure 3-1 shows the spatial distribution of the adopted 1000km² catchments for the derivation of ARF in the NSW and ACT (Sinclair Knight Merz, 2010). For NSW and ACT, it can be seen that the spatial coverage is generally very good in coastal regions and adequate along the Murray River and in the eastern part of the inland region, but there is poor coverage in other inland areas due to sparse spacing of rainfall gauges. Similar characteristics in the spatial distribution of circular catchments were also identified in other regions of Australia, with good coverage in areas where population density is relatively high (generally along the coast and in fertile inland regions) but much lower in areas of low population density (and normally low rainfall).

In the study for each individual region (except Tasmania), rainfall gauge data and circular catchments were also adopted from an "overlap" region, which included all gauges that were in rainfall districts along the border of the region to be analysed. As an example, Figure 3-1 shows rainfall gauges and circular catchments that extend into Queensland, Victoria and South Australia, which were included in the analysis for NSW and ACT.

Table 3-1 Rules of selection for circular "catchments"

Size of circular "catchment" (km²)	Required number of concurrent gauges	Maximum allowed proportion closest to a single gauge
125	3	67%
250	3	67%
500	3	67%
1000	4	50%
2000	6	33%
4000	10	33%
8000	18	33%

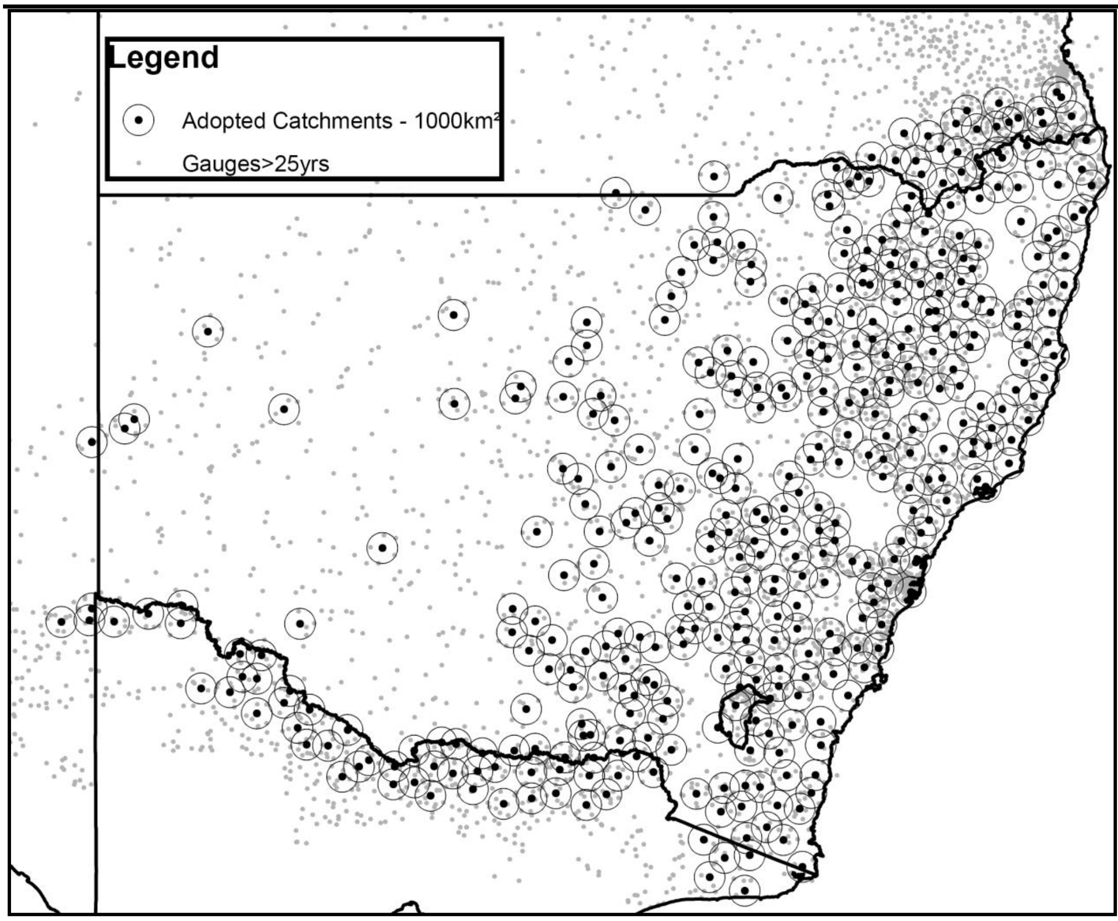

Figure 3-1 Circular catchments of 1000km² used for derivation of ARF in NSW and ACT region

Table 3-2 Number of circular catchments of various sizes for each state

Size of circular "catchment" (km²)	Victoria	Tasmania	South Australia *	Western Australia	Queensland	NSW & ACT
50				Not provided in report	48	
125	119	68	101		97	199
250	178	68	168		74	548
500	157	88	151		219	605
1000	180	74	97		147	403
2000	96	44	55		78	239
4000	52	26	25		33	131
8000	30	12	11		12	53

* Sourced from additional material outside of published report

3.3. Extraction of annual maximum rainfall series

Point rainfall series

The maximum point rainfalls for a catchment are represented by the maximum rainfall events observed at different gauge locations within the catchment. The point rainfall series at the different gauge locations are then combined through a regional frequency analysis to determine the average point rainfall frequency curve for that catchment.

Software routines were developed to extract annual maxima, utilising as much of the available information as possible. Accumulated rainfalls were disaggregated and missing rain periods were checked for the occurrence of an annual maximum by comparing with rainfall records at nearby stations. Constraints were imposed to safeguard that the available information at each gauge is adequate for an accurate assessment of the point rainfall frequency curve.

Areal rainfall series

A number of techniques are available to estimate mean annual rainfall for a catchment from specific point measurements at rain gauge locations in and around the catchment. The most commonly used techniques include Thiessen polygons, spline surfaces, polynomial surfaces, kriging and inverse-distance weights (Tabios and Sales, 1985; Luk and Ball, 1997). Considering the computational effort involved in analysing a large number of combinations of stations, the ARF derivation in all of the CRC-FORGE projects adopted a computationally simpler approximation to the conventional Thiessen weighting procedure. In this procedure, the 'catchment' was divided into a finer grid mesh, and weights for gauging stations were computed by assigning each grid cell within the catchment to the nearest station. As the final ARF results were based on the analysis of a large number of catchments, the averaging process was expected to compensate for any small errors that may have been introduced through the spatial averaging procedure.

Areal rainfalls were calculated for overlapping periods of 1, 2, 3, 4 and 5 days. The areal rainfall estimates for different events may be based on different combinations of stations, depending on the availability of data. The accuracy of the estimate generally depends on the number and representativeness of stations used to account for the spatial rainfall variability, and on the spatial correlation structure of the storm. Hence, some constraints were imposed to safeguard the accuracy of the estimate by having an adequate number of stations with appropriate spatial coverage. Areal rainfalls were estimated only for those periods that satisfy the minimum criteria, as set out in Table 3-1.

While some small errors in individual ARF values may arise from the use of non-concurrent data sets in the computation of the point and areal rainfall frequency curves, the subsequent averaging process should also compensate for these errors.

3.4. Frequency analysis of point and areal rainfall series

A number of frequency distributions have been used to fit extreme rainfalls, namely, log-normal, Gumbel, exponential, Log-Pearson III and GEV distribution. The GEV distribution fitted by L-moments (Hosking *et al.*, 1985) or higher order L-moments (Wang, 1997) have gained wider acceptance among researchers in recent times. The three-parameter Generalised Extreme Value (GEV) distribution fitted by linear combinations of probability-weighted moments (or L-moments) was adopted in the derivation of long duration ARF in all of the CRC-FORGE projects. This procedure is considered to be robust and efficient and has been shown to suffer less from the effects of sampling variability and data outliers than the conventional distribution fitting procedures (Hosking *et al.*, 1985; Hosking, 1990).

For areal rainfall, the parameters of the distribution are estimated from a single series. However, for point rainfall, an average point rainfall frequency curve condensing information from the annual maximum point rainfall series at all gauge locations in the catchment needs to be estimated. For this purpose, a *regional* procedure of fitting a GEV distribution was applied; here 'region' refers to the catchment under study. In this approach, L-moments calculated for each individual station were weighted in proportion to the record length to obtain regionally weighted L-moments. A GEV distribution was then fitted to the regional L-moments by the method of probability weighted moments (Hosking and Wallis, 1990).

3.5. Derivation of areal reduction factors

Once the areal and average point rainfall frequency curves (durations of 1 to 5 days) have been derived for a sample catchment, ARF were calculated by dividing areal rainfall estimates by the corresponding point rainfall estimates for a range of AEP (1 in 2 to 1 in 100). In the absence of clear evidence for disparity, the correction factors involved in converting rainfall amounts pertinent to 'restricted' to 'unrestricted' durations were assumed to be the same for both areal and point rainfall (Dwyer and Reed, 1995). Thus, it was assumed that the ARF values computed for 1, 2, 3, 4 and 5 days can be used directly for 'unrestricted' durations of 24, 48, 72, 96 and 120 hours.

Software tools were developed to facilitate the computation of ARF. The first set of tools assists with finding a set of circular 'catchment' locations that satisfy the specified conditions. Given the centroid and radius of a selected circular catchment, the main program scans a database and selects the data files necessary for computation, extracts an annual maximum areal rainfall series from daily data, derives areal and point rainfall frequency curves and calculates ARF for a range of durations from 24 to 120 hours and AEP from 1 in 2 to 1 in 100.

In situations where visual examination of ARF across a particular region provided reasonable suspicion of spatial variation in ARF values, a statistical test for regional variability was undertaken. In such cases, the study area was divided into several regions on the basis of meteorological considerations and then statistical tests were performed, to identify whether the regional mean values of ARF are significantly different. No statistically significant evidence of heterogeneity was identified in the Victorian, SA, Queensland or Tasmanian studies but the NSW and ACT region was found to have two separate regions that had ARF values that were demonstrated to be significantly different from one another using statistical tests. Western Australia was one homogenous region for annual ARF equations but was found to have two separate regions for seasonal ARF equations.

The representative ARF for a homogenous region were determined as the mean of the sample

ARF values for respective areas, durations and AEP. These mean ARF estimates form the basis for design values for the region.

3.6. Design values of areal reduction factors

The *design values* of ARF need to be based on a functional relationship established between sample mean values of ARF and the variables of catchment area, rainfall duration and AEP. This allows the definition of ARF for variable values other than those sampled, as well as reasonable extrapolation beyond the range of sampled values. A single multivariate function also allows a smooth transition of ARF values between areas, durations and AEP.

In the Victorian CRC-FORGE project (Siriwardena and Weinmann, 1996a,b), a number of candidate functions were evaluated for their suitability. As the sample of ARF values for areas less than 100 km^2 is generally very limited, special attention needs to be given to the tail behavior of the fitted function. The function has to approach an ARF value of 1.0 at an area considered to be of practical significance; this terminal area could be expected to increase with duration (e.g. 1 to 10 km^2 for the range of durations from 24 to 120 hours).

The preliminary results for Victoria indicated a clear tendency for ARF values to decrease with decreasing AEP, but also an increase in sampling variability with decreasing AEP. Compared to the variation of ARF with catchment area and rainfall duration, the variation with AEP has to be considered as a secondary effect. The design relationship for ARF was therefore derived in two stages: first the relationship of ARF with catchment area and rainfall duration was established for an AEP of 0.5; a function representing the variation with AEP was then derived and added as a correction term. Again, the nature and magnitude of this correction should be plausible and consistent with known characteristics of extreme rainfall events.

The derivation of long duration ARF undertaken in CRC-FORGE projects for the remaining regions adopted the functional forms adopted by Siriwardena and Weinmann (1996 a, b) for Victoria, without re-examining alternative functional forms. They also adopted virtually identical approaches of initially fitting the ARF with catchment area and rainfall duration for an AEP of 0.5. In SA, Tasmania and the southern region of NSW and ACT[2], the function representing the variation in AEP was then derived and added as a correction term to the ARF equation for an AEP of 0.5. In Queensland and the northern region of NSW[3] there was no evidence of any dependence of ARF with AEP, so no correction term with AEP was required and the equation fitted for an AEP of 0.5 was adopted without modification. The seasonal curves for Western Australia included a correction term to the ARF for AEP but the annual curves for Western Australia did not.

The equations adopted for the regions of different states are presented in Section 4.

[2] Represented by the overlap of the region where the Generalised South East Australia Method for estimation of Probable Maximum Precipitation is applicable with the state boundary of NSW

[3] Represented by the overlap of the Generalised Tropical Storm Method Revised for estimation of Probable Maximum Precipitation is applicable with the state boundary of NSW

3.7. Interim short duration areal reduction factors

Analysis of ARFs for shorter duration events (less than 18 hour duration) in Australia is considerably less extensive than for long duration events (18 to 120 hour duration). As an interim measure, equations for short duration events have been derived that produce consistency with the long duration ARF equations in each region and that assume the 1 hour duration ARF values derived in the United Kingdom Flood Studies report are also applicable to Australia (Natural Environmental Research Council, 1975). To ensure consistency of ARFs across all durations less than 18 hours for all areas, parameters of the interim short duration curves for some regions were re-derived as part of the current project. The re-derived interim curves resulted in relatively minor differences to the interim curves that were produced by previous authors.

3.8. Variations in the method between States

There was some variation in the way that the CRC-FORGE method was applied in different states. In each state, an assessment of regionality was carried out, and in New South Wales and Western Australia this was found to be important. This is discussed further in Sections 4.3 and 4.3. For Western Australia, a seasonality component was found as well, so summer equations for the two regions were developed, along with one winter equation (Section 4.3). In Tasmania, the interim short duration have not been developed, and the Victorian equations are used (Section 4.2).

4. Results

This section details the results found in analysis across Australia. The equations for both long and short duration ARF have been summarised for each state. The long duration equations all have the same form as Equation 1 while the interim short duration equations take the form of Equation 2.

Long duration equation

$$Areal\ reduction\ factor = Min\{1, [1 + a(Area^b + c\log_{10} Duration)Duration^d + eArea^f Duration^g (0.3 + \log_{10} AEP)]\}$$

Where

Area = Area of interest in km²

Duration = Storm duration in hours (between 18 and 120 hours)

AEP = Annual exceedance probability as a fraction between 0.5 and 0.0005

Equation 1

Interim short duration equation

$$Areal\ reduction\ factor = Min\{1, [1 + a(Area^b + c) + d(Area^e)(f - \log_{10} Duration)]\}$$

Where

Area = Area of interest in km²

Duration = Storm duration in hours (between 1 and 18 hours)

Equation 2

In general, the ARF equations fitted for the long durations (24 to 120 hours) in each region fitted the mean values derived for the set of circular catchments of a given area in that region to within 1%. Statistical measures of the quality of the fit of the ARF equation to the mean values from the circular catchments within region are provided in most of the regional reports.

4.1. Victoria

The Victorian analysis was completed in 1996 (Siriwardena and Weinmann, 1996a) and is summarised by Equation 3 and Equation 4. Figure 4-1 plots the equations for an AEP of 0.5 and all durations between 1 and 120 hours.

Long duration equation

$$ARF = Min\{1, [1 - 0.4(Area^{0.14} - 0.7\log_{10} Duration)Duration^{-0.48} + 0.0002Area^{0.4}Duration^{0.41}(0.3 + \log_{10} AEP)]\}$$

Equation 3

Interim short duration equation

$$ARF = Min\{1, [1 - 0.10(Area^{0.14} - 0.879) - 0.029(Area^{0.233})(1.255 - \log_{10} Duration)]\}$$

Equation 4

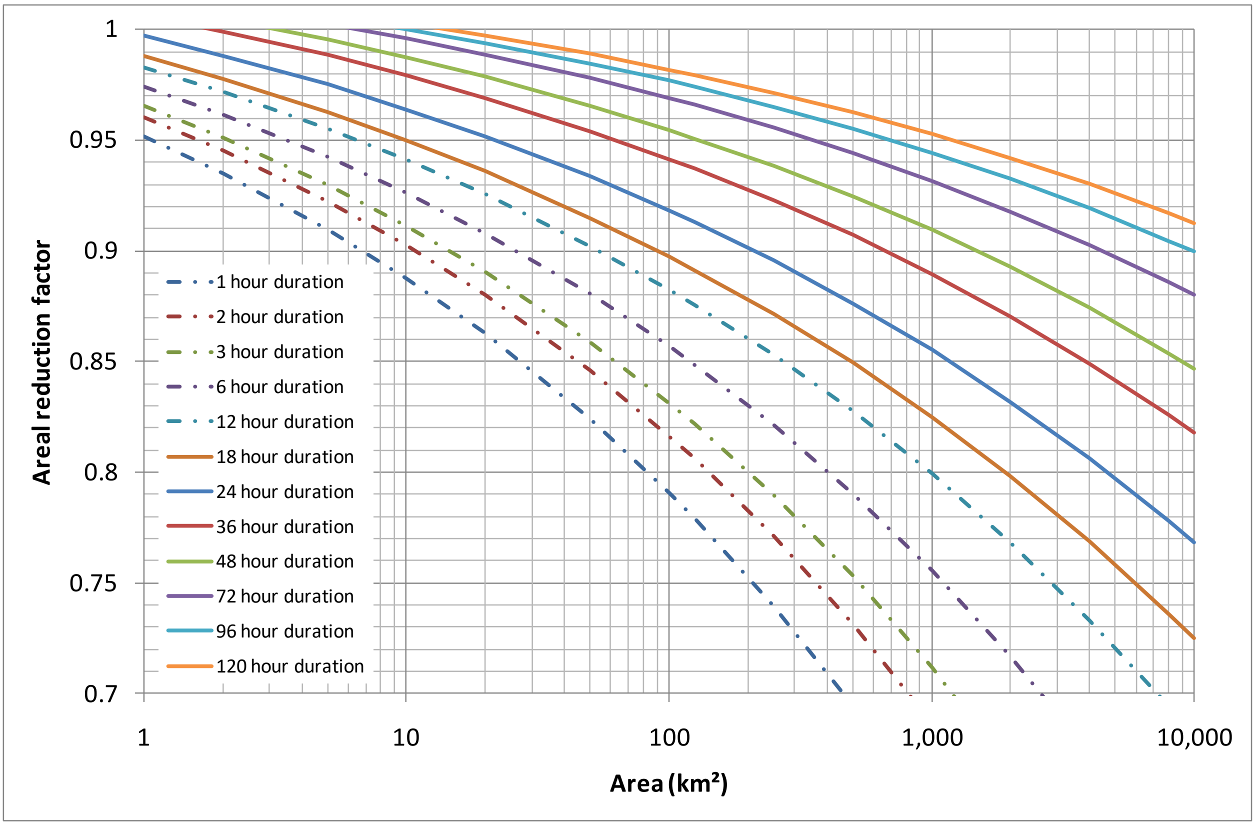

Figure 4-1 ARF in Victoria for AEP = 0.5 for varying rainfall durations

4.2. Tasmania

The CRC-FORGE assessment in Tasmania was completed in 1998 by the Hydro Electric Corporation Consulting Business Unit (Gamble et al, 1998). The long duration ARF equations can be seen in Equation 5 and are illustrated in Figure 4-2.

Gamble *et al.* (1998) had originally recommended the adoption of the interim short duration equation derived by Siriwardena and Weinmann (1996a) for use in Tasmania. However, the parameters of interim short duration equation (Equation 6) were re-derived (see Appendix A) to reduce the implausibly large separation between the interim curve for 12 hours and the long duration curve for 18 hour duration.

Long duration equation

$$ARF = Min\{1, [1 - 0.105(Area^{0.216} - 0.882\log_{10} Duration)Duration^{-0.343} + 0.0012Area^{0.223}Duration^{0.335}(0.3 + \log_{10} AEP)]\}$$

Equation 5

Interim short duration equation

$$ARF = Min\{1, [1 - 0.0342(Area^{0.222} - 1.094) - 0.0291(Area^{0.302})(1.29 - \log_{10} Duration)]\}$$

Equation 6

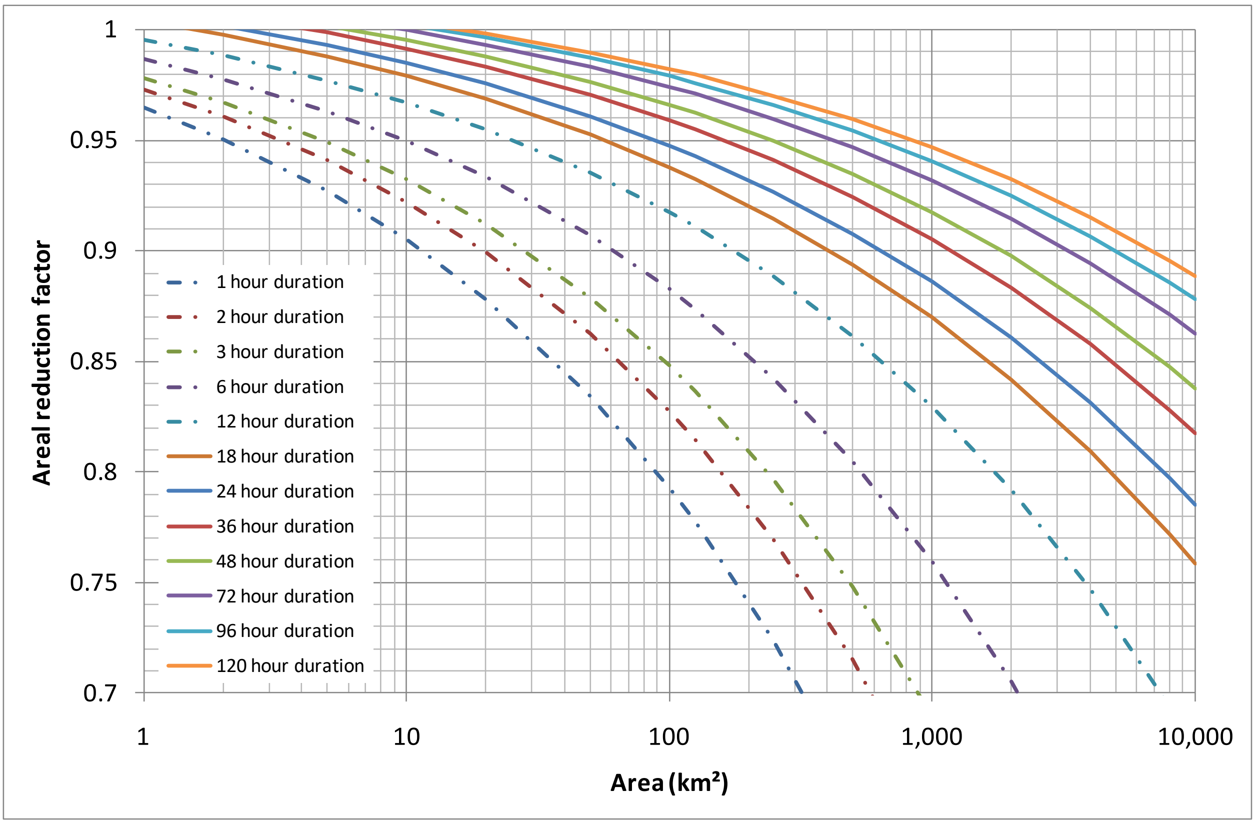

Figure 4-2 ARF for Tasmania for AEP = 0.5 for varying rainfall durations

4.3. South Australia

The application of the CRC-FORGE method in South Australia (SA) was completed in 2000 for the SA Water Corporation (Sinclair Knight Merz, 2000). Both long duration (Equation 6) and interim short duration (Equation 7) equations were developed. The resultant curves for an AEP of 0.5 can be seen in Figure 4-3.

Long duration equation

$$ARF = Min\{1, [1 - 0.14(Area^{0.22} - 1.09\log_{10} Duration)Duration^{-0.42} + 0.0001Area^{0.35}Duration^{0.5}(0.3 + \log_{10} AEP)]\}$$

Equation 7

Interim short duration equation

$$ARF = Min\{1, [1 - 0.015(Area^{0.014} - 6.12) - 0.05(Area^{0.18})(2.48 - \log_{10} Duration)]\}$$

Equation 8

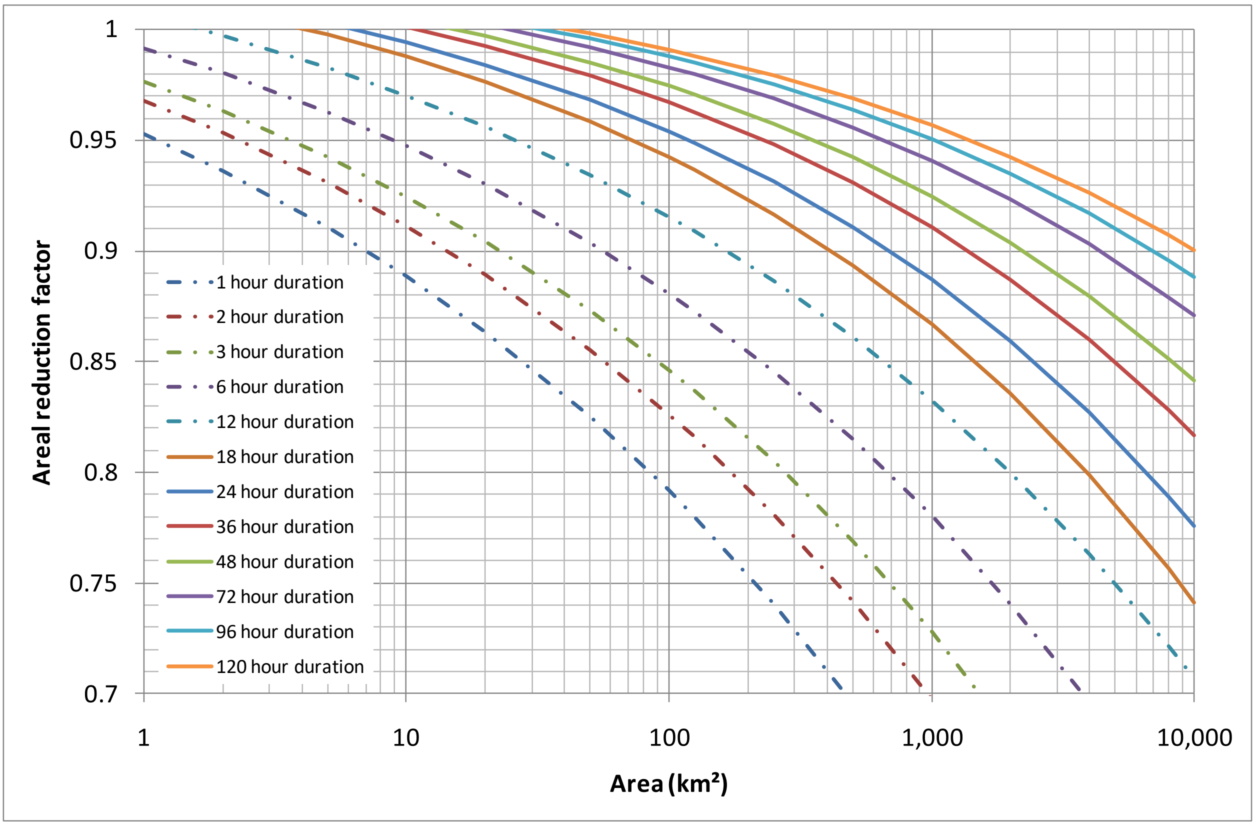

Figure 4-3 ARF for South Australia for AEP = 0.5 for varying rainfall durations

4.4. Western Australia

ARF curves for WA were derived as part of the CRC-FORGE project undertaken by Durrant and Bowman (2004). Both annual and seasonal curves were derived, with some regionality found to be important in the seasonal curves.

4.4.1. Annual curves

The annual long duration equation (Equation 8) for Western Australia was found to be independent of AEP, so the second part of the general form of the equation (Equation 1) was removed.

Sinclair Knight Merz (2012) derived an interim short duration equation. However, the parameters of interim short duration equation can be seen (Equation 9) was re-derived (see Appendix A) to avoid the 12 hour duration interim ARF equation crossing over the 18 hour long duration equation for the corresponding region from Durrant and Bowman (2004).

Figure 4-6 illustrates the annual long and interim short duration ARF curves, for an AEP of 0.5, found for all of Western Australia.

Long duration equations

- All seasons – All of WA

$$ARF = Min\{1, [1 - 0.13(Area^{0.21} - 0.56\log_{10} Duration)Duration^{-0.45}]\}$$

Equation 9

Interim short duration equation

- All seasons – All of WA

$$ARF = Min\{1, [1 - 0.0518(Area^{0.257} - 0.553) - 0.0231(Area^{0.333})(0.64 - \log_{10} Duration)]\}$$

Equation 10

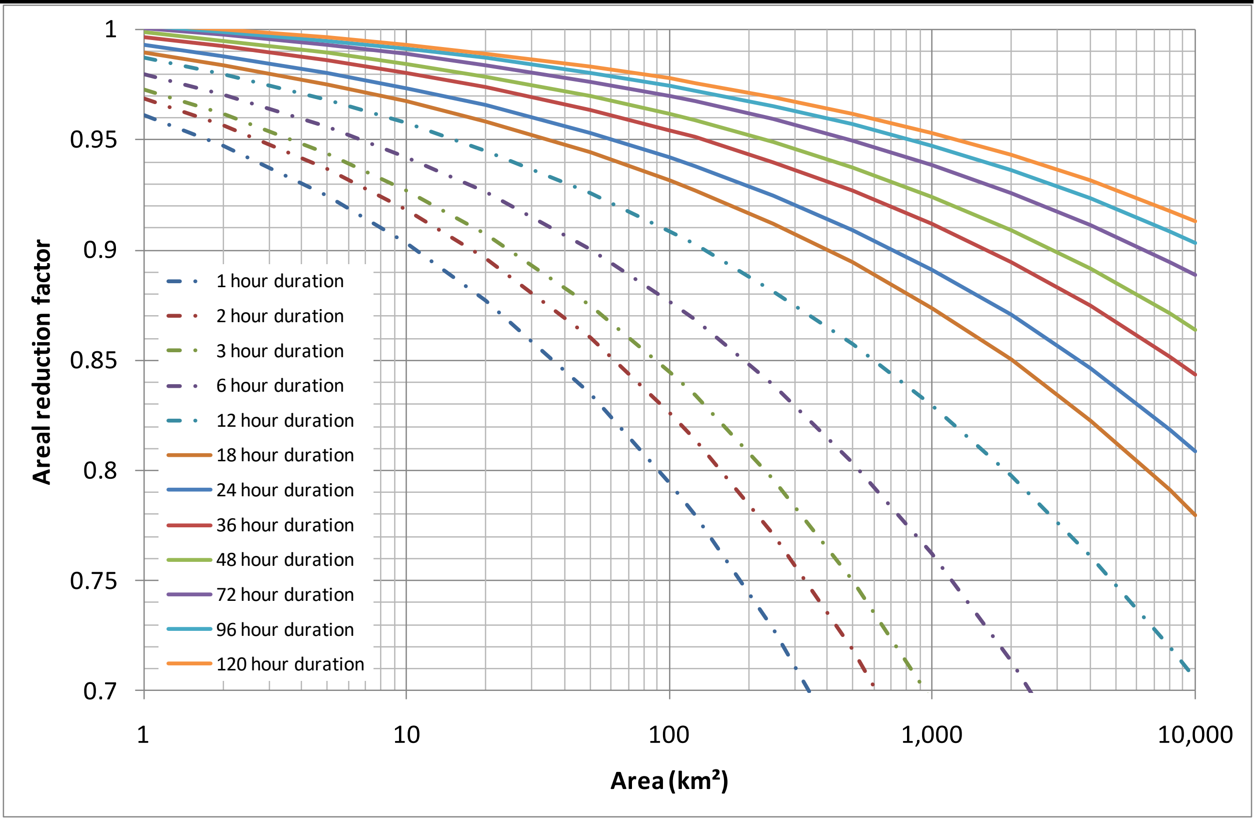

Figure 4-4 Annual ARF curves for Western Australia for varying rainfall durations

4.4.2. Seasonal curves

In WA, it was found that there was a difference between the ARF that applied between the summer (October to March) and winter (April to September) seasons. For the summer (October to March season), it was demonstrated that there were two homogeneous sub-regions for definition of ARF within WA, with the ARF found to be statistically significantly different between the south west of WA and the remainder of WA. Only one sub-region (representing all of WA) was adopted for winter (April to September) ARF, resulting in a total of three equations for long duration ARF. The demarcation of the South-west region of WA was based on the 700mm mean annual rainfall isohyets as seen in Figure 4-5.

The seasonal equations produced by Durrant and Bowman (2004) are shown in Equation 10 for the summer season (October to March) in the south-west of WA; Equation 11 for the summer season (October to March) in the rest of WA; and Equation 12 for the winter season (April to September) across all of WA.

The interim short duration equations derived as a part of the *Australian Rainfall and Runoff Revision Project 6* (SKM, 2012) are not appropriate for use with the seasonal estimates.

Figure 4-6 illustrates the summer ARF curves, for an AEP of 0.5, found for South-west WA; Figure 4-7 illustrates the summer ARF curves found for the rest of WA; and Figure 4-8 illustrates the winter ARF curves for all areas of WA.

Long duration equations

- Summer – South-west WA region

$$ARF = Min\{1, [1 - 0.11(Area^{0.25} - 0.35\log_{10} Duration)Duration^{-0.48} - 0.1408Area^{0.01}Duration^{-0.52}(0.3 + \log_{10} AEP)]\}$$

Equation 11

- Summer – Rest of WA

$$ARF = Min\{1, [1 - 0.23(Area^{0.17} - 0.57\log_{10} Duration)Duration^{-0.40} - 0.0287Area^{0.21}Duration^{-0.41}(0.3 + \log_{10} AEP)]\}$$

Equation 12

- Winter – All of WA

$$ARF = Min\{1, [1 - 0.11(Area^{0.24} - 0.3\log_{10} Duration)Duration^{-0.52} + 0.00040Area^{0.32}Duration^{0.38}(0.3 + \log_{10} AEP)]\}$$

Equation 13

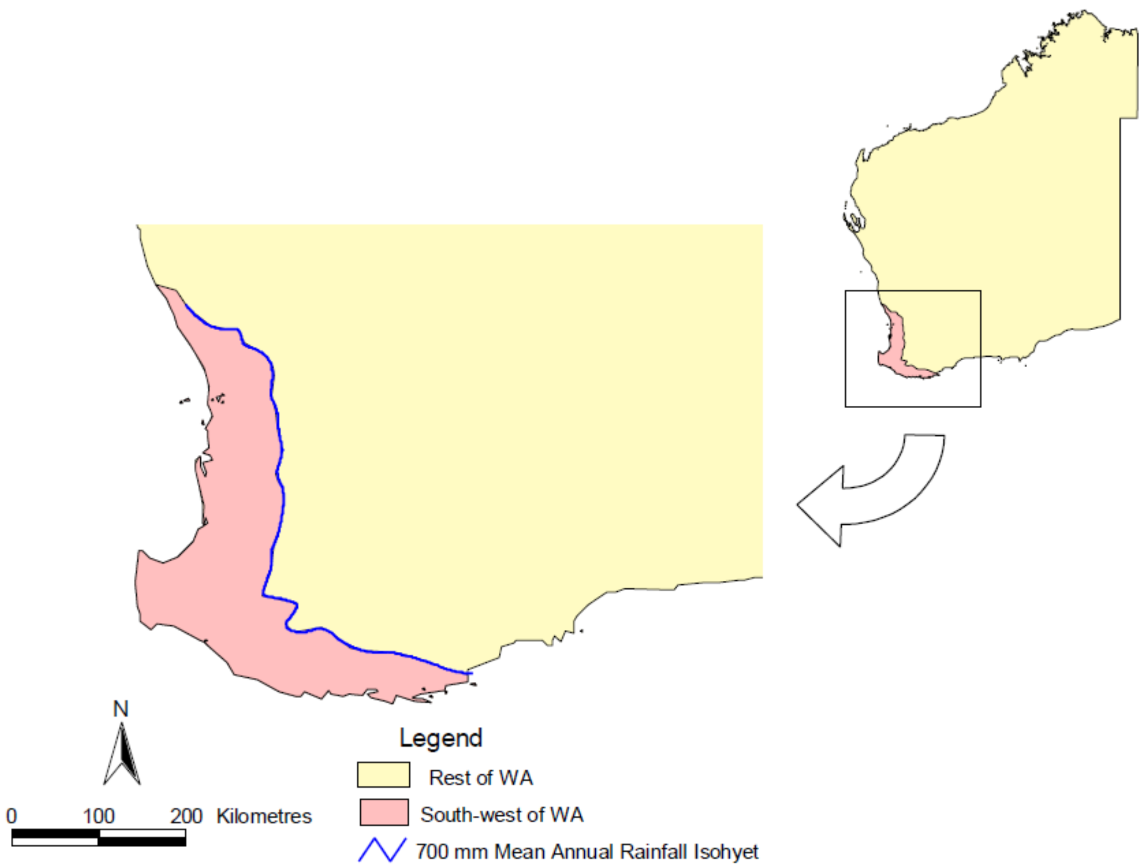

Figure 4-5 Summer ARF regions (demarcation of South-west region with greater than 700 mm mean annual rainfall) (Source: Durrant, J and Bowman, S, 2004, *Estimation of rare design rainfalls for Western Australia: Application of the CRC-FORGE method,* Department of Environment, Government of Western Australia, Surface Water Hydrology Report Series, Report No. HY17, p. 50, Figure 6.5)

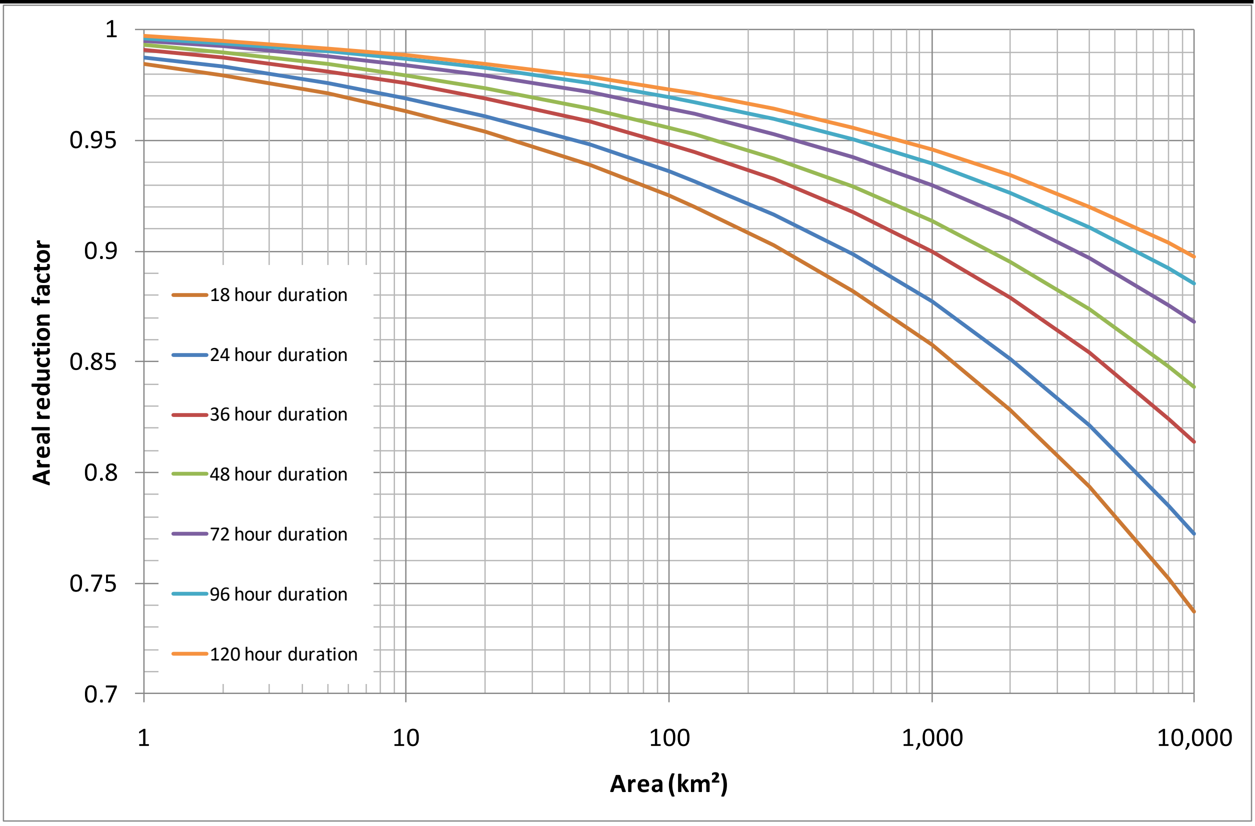

Figure 4-6 Summer ARF for the south-west Western Australia region for AEP = 0.5 for varying rainfall durations

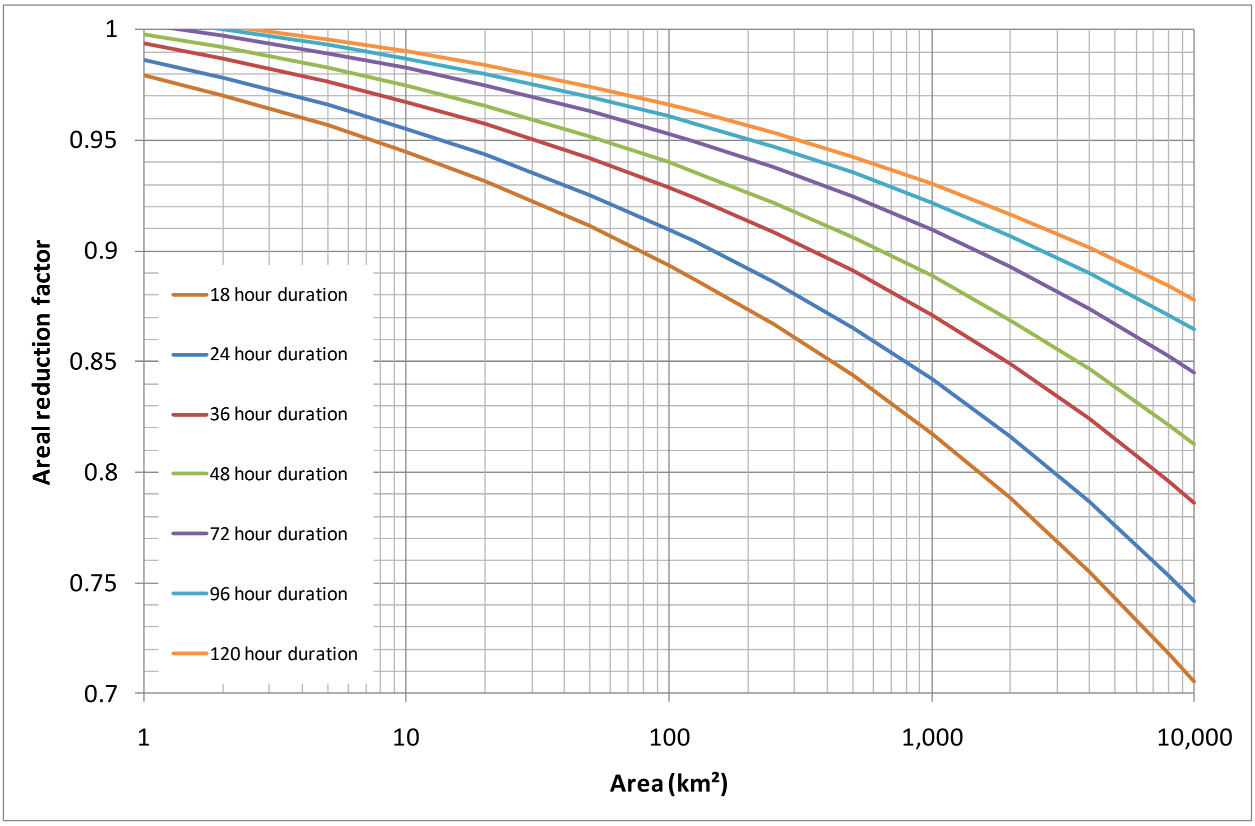

Figure 4-7 Summer ARF for the rest of Western Australia for AEP = 0.5 for varying rainfall durations

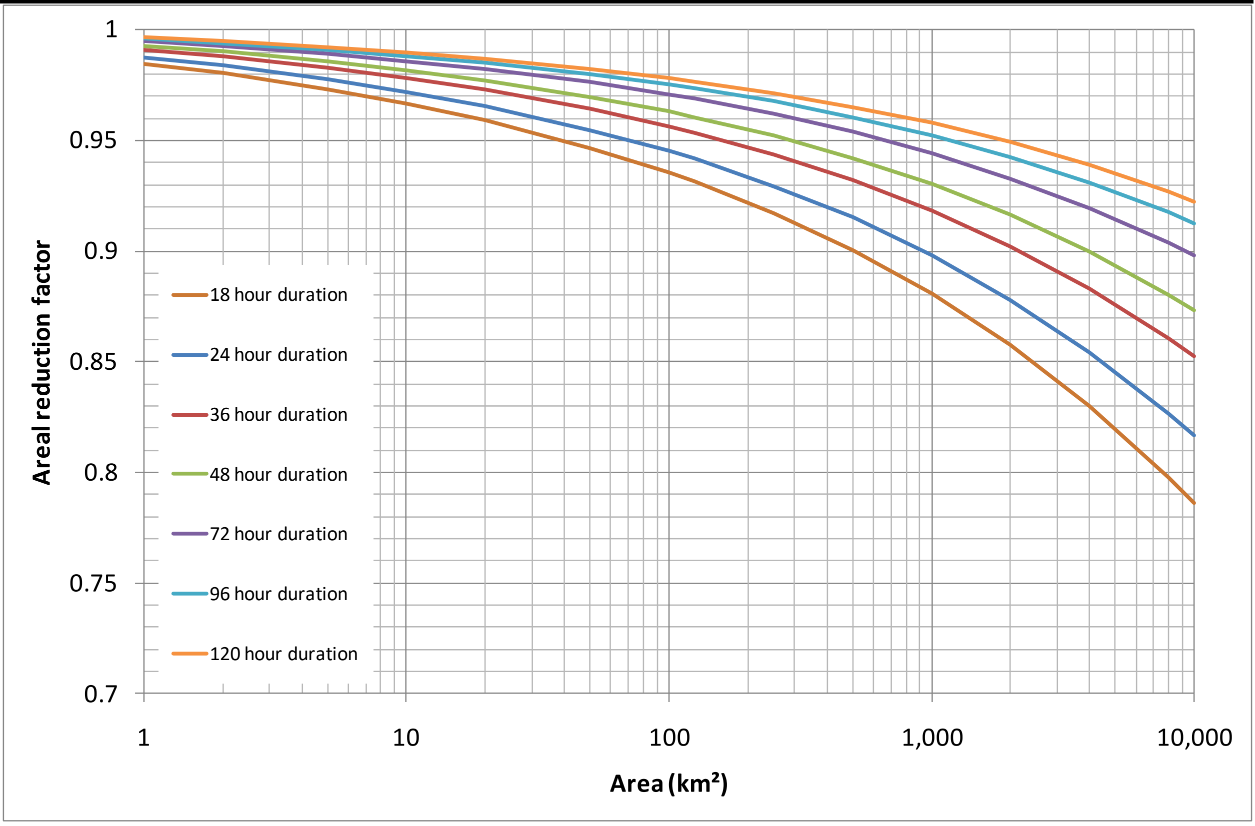

Figure 4-8 Winter ARF for Western Australia for AEP = 0.5 for varying rainfall durations

4.5. Queensland

The Queensland CRC-FORGE project and associated long duration ARF equation was completed by Hargraves (2005) and is detailed in Equation 13. It was found that the relationship was not dependent on AEP, so the second part of the general form of the equation (Equation 1) was removed.

The interim short duration equation (Equation 14) for Queensland was re-derived to avoid the 12 hour duration interim ARF equation crossing over the 18 hour long duration equation for the corresponding region from Hargraves (2005). The re-derivation of the interim short duration equation is described in Appendix A. Figure 4-2 illustrates the resultant ARF curves.

Long duration equation

$$ARF = Min\{1, [1 - 0.2257(Area^{0.1685} - 0.8306\log_{10} Duration)Duration^{-0.3994}]\}$$

Equation 14

Interim short duration equation

$$ARF = Min\{1, [1 - 0.0539(Area^{0.205} - 0.925) - 0.0246(Area^{0.313})(1.16 - \log_{10} Duration)]\}$$

Equation 15

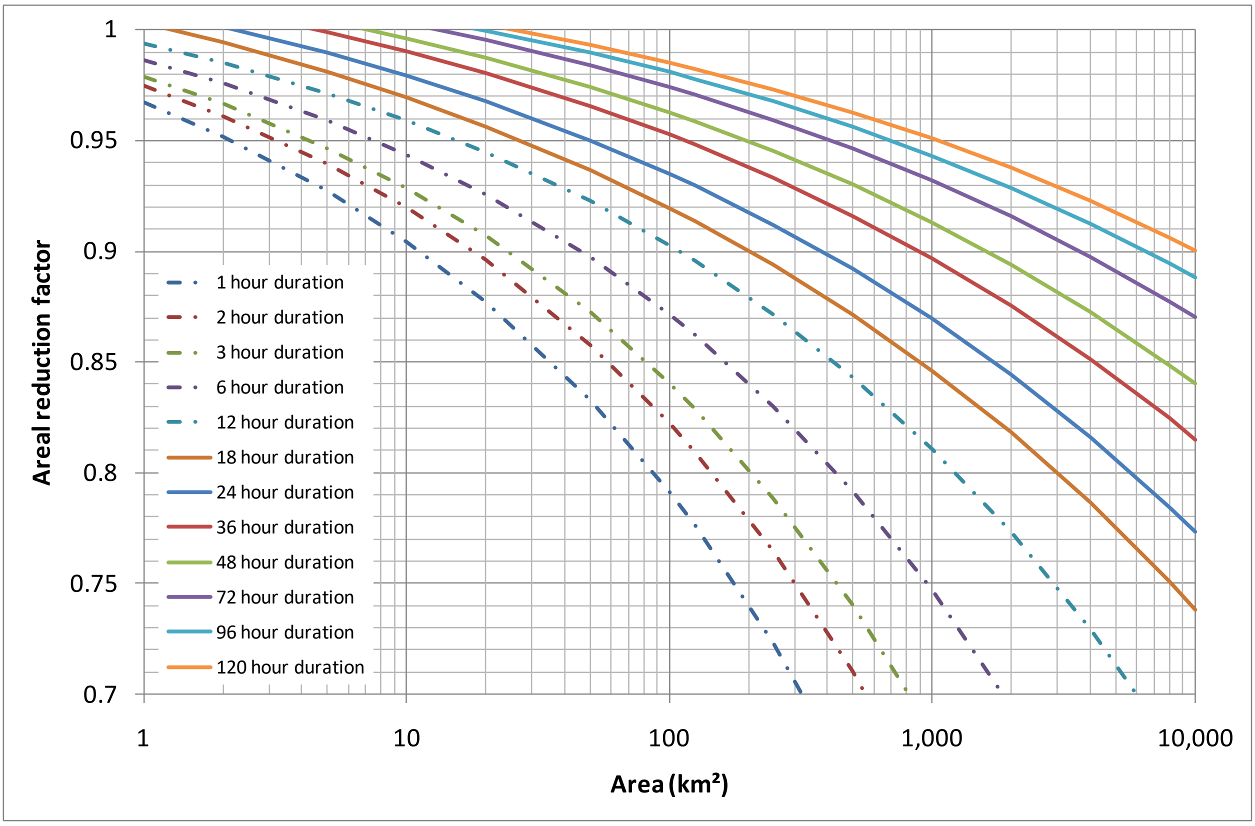

Figure 4-9 ARF for Queensland for varying rainfall durations

4.6. New South Wales and the Australian Capital Territory

For New South Wales (NSW) and the Australian Capital Territory (ACT), the CRC-FORGE project was completed in 2010 for ACTEW AGL and State Water (Sinclair Knight Merz and State Water, 2010).

It was demonstrated that there were two homogeneous sub-regions for definition of ARF within NSW and ACT, with the ARF found to be statistically significantly different between the southern and northern sub-regions of NSW and ACT. The boundary between the northern and southern regions was defined as the boundary between the applicability of the Generalised Southeast Australian Method (GSAM) and Generalised Tropical Storm Method Revised (GTSM-R) regions for Probable Maximum Precipitation, as shown in Figure 4-10. Two separate sets of equations were developed for both the long and interim short duration equations to represent ARF in each of the GSAM and GTSM-R regions in NSW and ACT.

The GSAM region equation follows the same form as that in Victoria and is shown in Equation 15. In the GTSM-R zone, like in Queensland, it was found that there was little dependence on AEP, so the second half of the equation was removed (Equation 16).

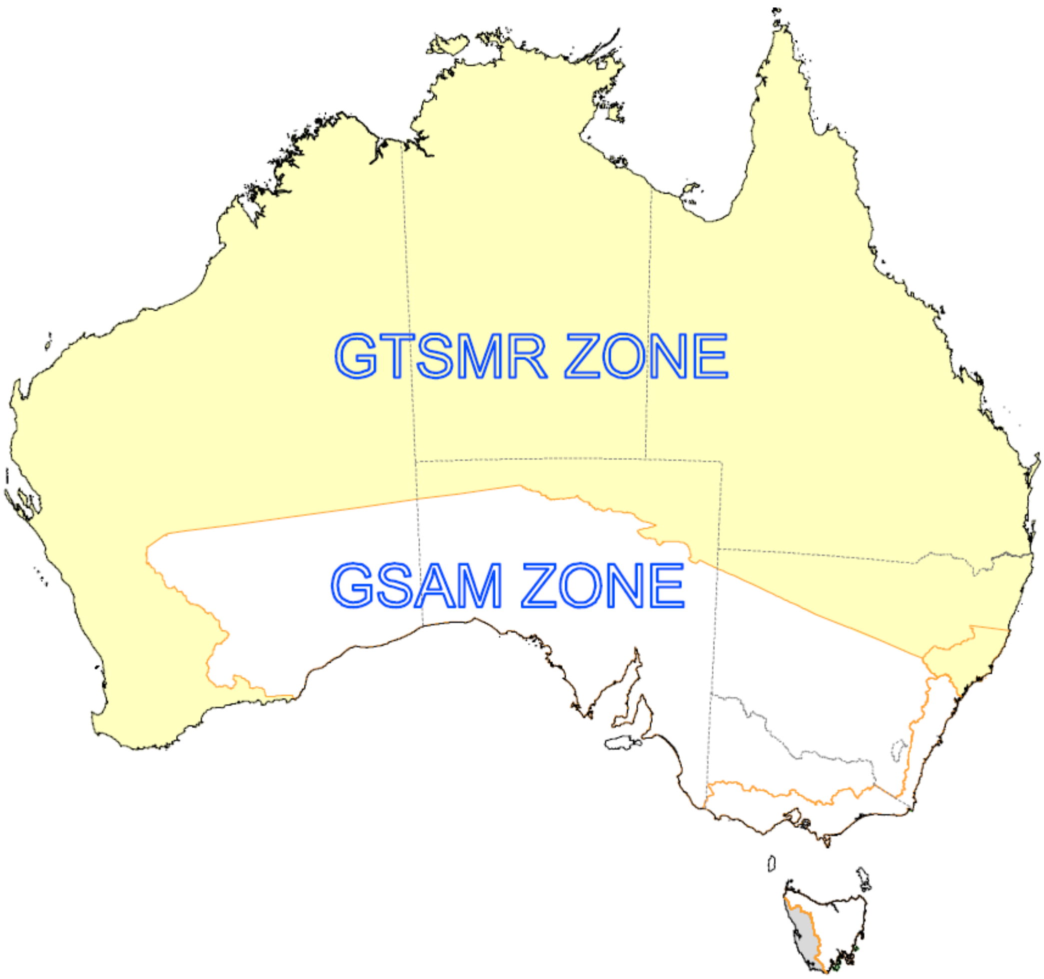

Figure 4-10 The area of Australia relevant to the GTSM-R (yellow) and the GSAM (white) (Walland *et al.*, 2003, p. 2).

Interim short duration equations for both regions were re-derived to avoid the 12 hour duration interim ARF equation crossing over the 18 hour long duration equation for the corresponding region from Sinclair Knight Merz and State Water (2010). The re-derivation of the equations is described in Appendix A.

Long duration equations

- GSAM Region

$$ARF = Min\{1, [1 - 0.23(Area^{0.183} - 0.91\log_{10} Duration)Duration^{-0.43} + 0.00048Area^{0.38}Duration^{0.21}(0.3 + \log_{10} AEP)]\}$$

Equation 16

- GTSM-R Region

$$ARF = Min\{1, [1 - 0.19(Area^{0.20} - 0.87\log_{10} Duration)Duration^{-0.412}]\}$$

Equation 17

Both equations applicable for:

- Catchment areas between 1 and 10,000km²
- Durations between 18 and 120 hours
- AEP between 0.5 and 0.0005 (i.e. between 1 in 2 and 1 in 2000)

Interim short duration equations

- GSAM Region

$$ARF = Min\{1, [1 - 0.0439(Area^{0.23} - 0.923) - 0.0255(Area^{0.309})(1.17 - \log_{10} Duration)]\}$$

Equation 18

- GTSM-R Region

$$ARF = Min\{1, [1 - 0.0449(Area^{0.207} - 1.032) - 0.0258(Area^{0.299})(1.37 - \log_{10} Duration)]\}$$

Equation 19

Both equations applicable for:

- Catchment areas between 1 and 10,000km²
- Durations between 1 and 18 hours
- AEP between 0.5 and 0.0005 (i.e. between 1 in 2 and 1 in 2000)

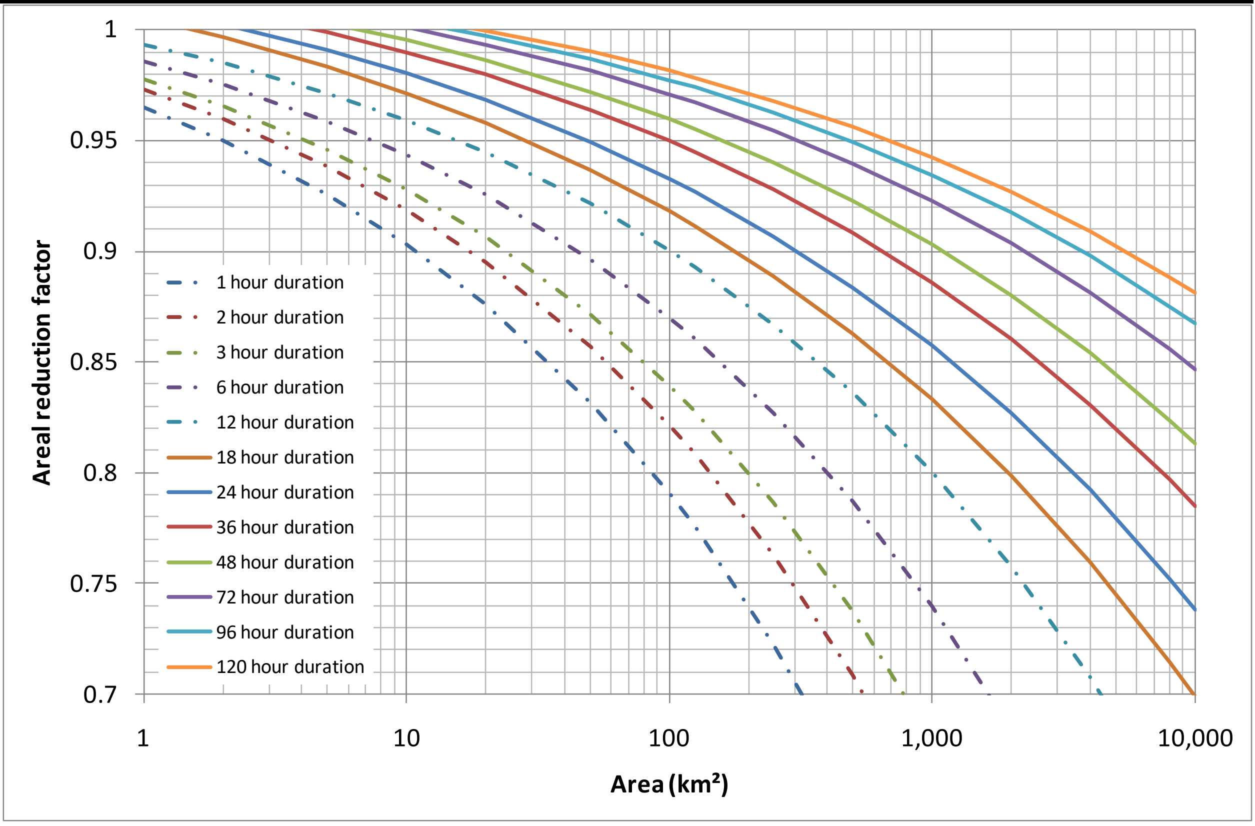

Figure 4-11 ARF in the NSW GTSM-R region for AEP = 0.5 for varying rainfall durations

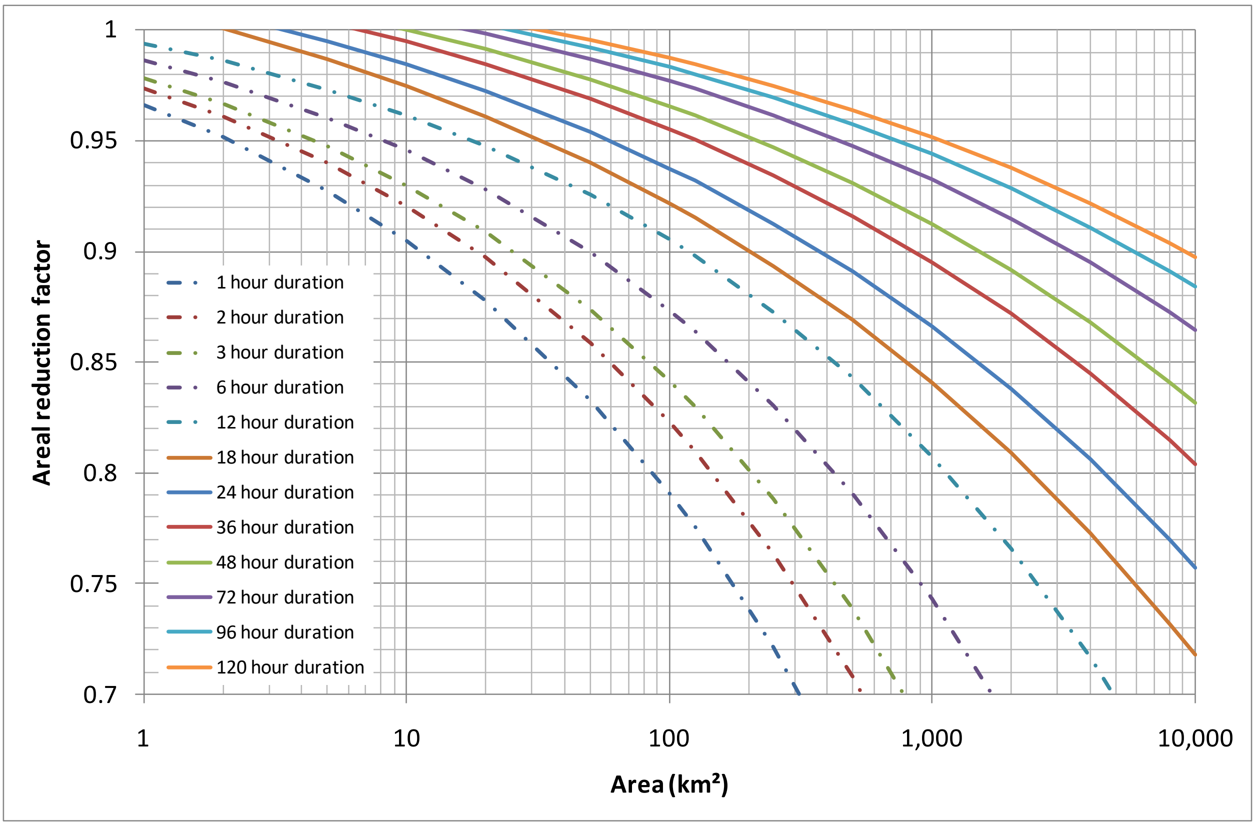

Figure 4-12 ARF in the NSW GSAM (including the ACT) region for AEP = 0.5 for varying rainfall durations

5. Discussion and Recommendations

5.1. Discussion

Figure 5-1 shows the regions that were adopted following the completion of all of the CRC FORGE projects. The boundaries selected are the outcome of a process driven by application of CRC-FORGE across individual states and territories, moderated by hydrometeorological factors that resulted in the definition of two regions within each of New South Wales and Western Australia.

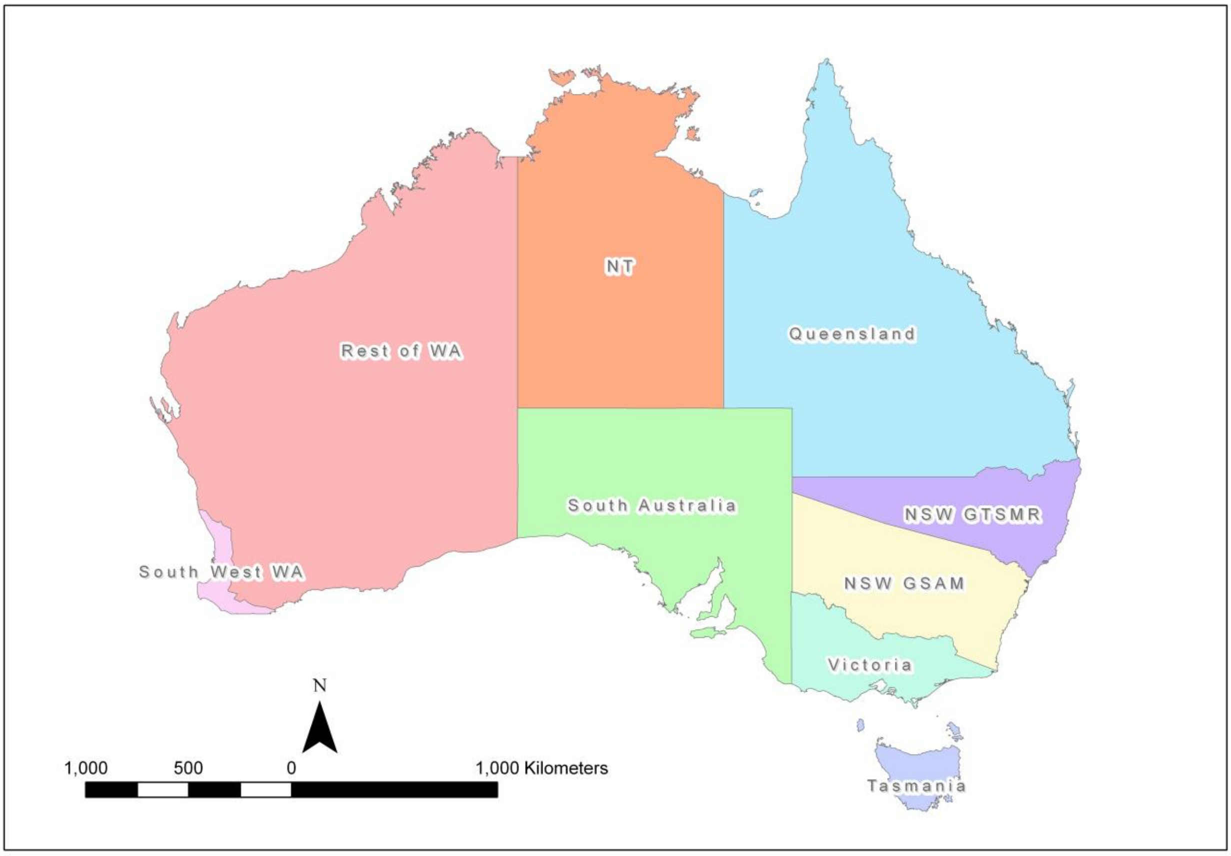

Figure 5-1 ARF zones after completion of all the CRC-FORGE projects

For regions in the South-Eastern part of Australia: Victoria, South Australia, Tasmania and the GSAM Region of NSW and ACT, the AEP of the event was found to be a statistically significant predictor of ARF. In all of these regions, the ARF reduces with increasing AEP of the design event. Figure 5-2 demonstrates this dependence for the 24 hour duration event in the NSW and ACT GSAM region, which is typical of the AEP dependence found also in Victoria, South Australia and Tasmania. It is possible that in these regions that the types of rainfall events that produce rainfall accumulations, across large catchment areas and at the more frequent end of the range considered (AEP of 0.5 to 0.2), are more likely to be frontal systems that tend to produce more consistent spatial patterns of rainfall due to their movement; while at events at the rarer end of the scale may be produced by extra-tropical storm systems that move more slowly and hence produce less consistent spatial patterns of rainfall. Further hydrometeorological interpretation of the cause of this AEP dependence would be warranted.

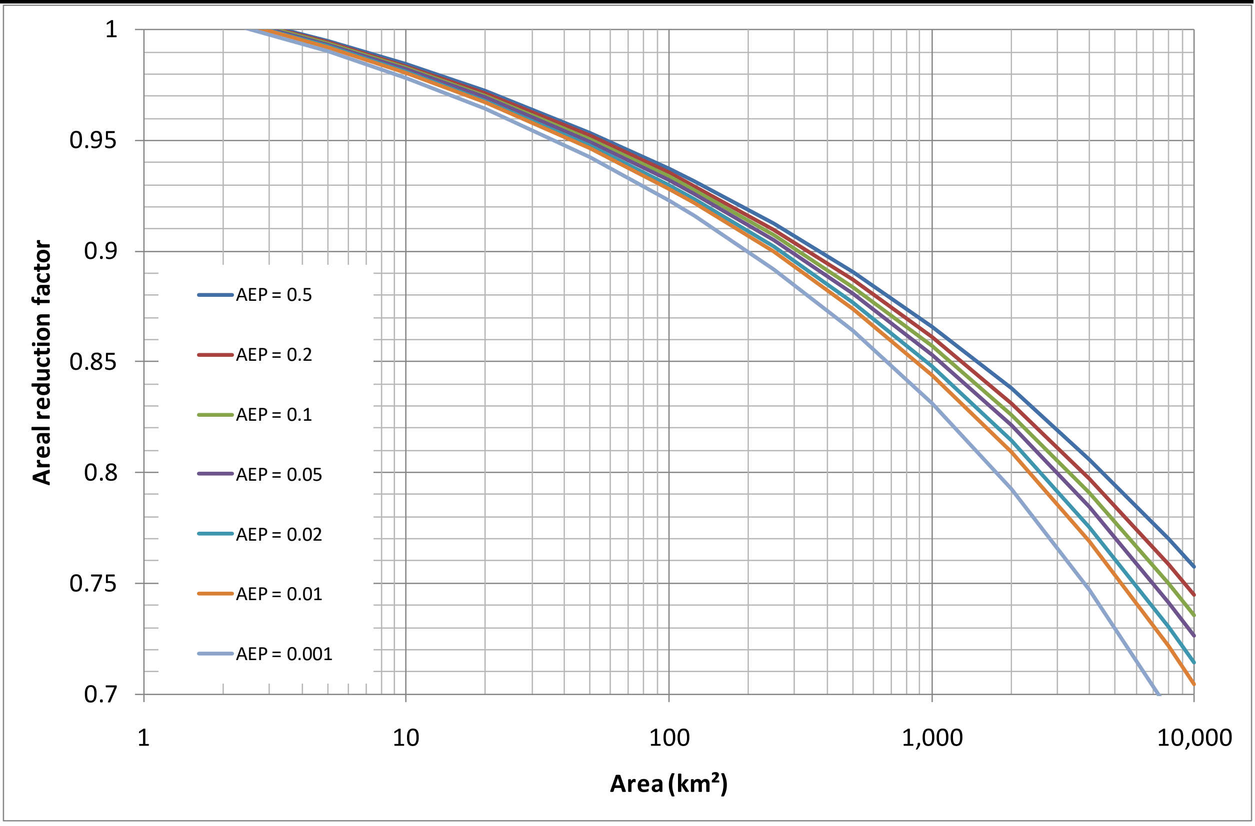

Figure 5-2 ARF curves for the NSW and ACT GSAM region for AEP between 0.001 – 0.5 for 24 hour duration

By contrast, there was found to be no statistically significant dependence between ARF and AEP for the Western Australia (annual curve), Queensland and NSW GTSM-R regions. This implies that there is little change in the mixture of meteorological causes that produce rainfall totals across the range of AEPs that were considered. The contrast in this response between South-Eastern Australia and the rest of Australia may be explained by differences in the mix of meteorological events that produce large and extreme rainfall events in each region.

Figure 5-3 compares the ARF curves between the different regions for 24 hour duration and an AEP of 0.5. For a given catchment area, there is a maximum variation in the ARF of approximately 0.05 between each of the regions, which is likely to be due to the underlying hydrometeorological variability between each of the regions. Figure 5-4 shows that there is a similar spread in ARF between each of the regions for more extreme rainfall events (AEP of 0.0005) and 24 hour duration. For catchment areas greater than 30km², all regions have ARF curves for 24 hour duration events that are lower than the ARF curve in ARR1987. The ARF equations from the CRC FORGE projects also provide ARF estimates for catchments up to 10,000 km² in area, whereas the ARR1987 curve applies for a maximum catchment area of 1,000 km². Since there are many catchments in the range of areas between 1,000 and 10,000 km² that would be employing rainfall based estimates of design floods, provision of curves across this range of catchment areas is useful in practice.

Figure 5-5 shows that for longer durations (in this case 72 hours) the ARF curves for the different regions become more clustered together than is the case for the 24 hour duration. ARR1987 did not provide ARF curves for durations longer than 24 hours.

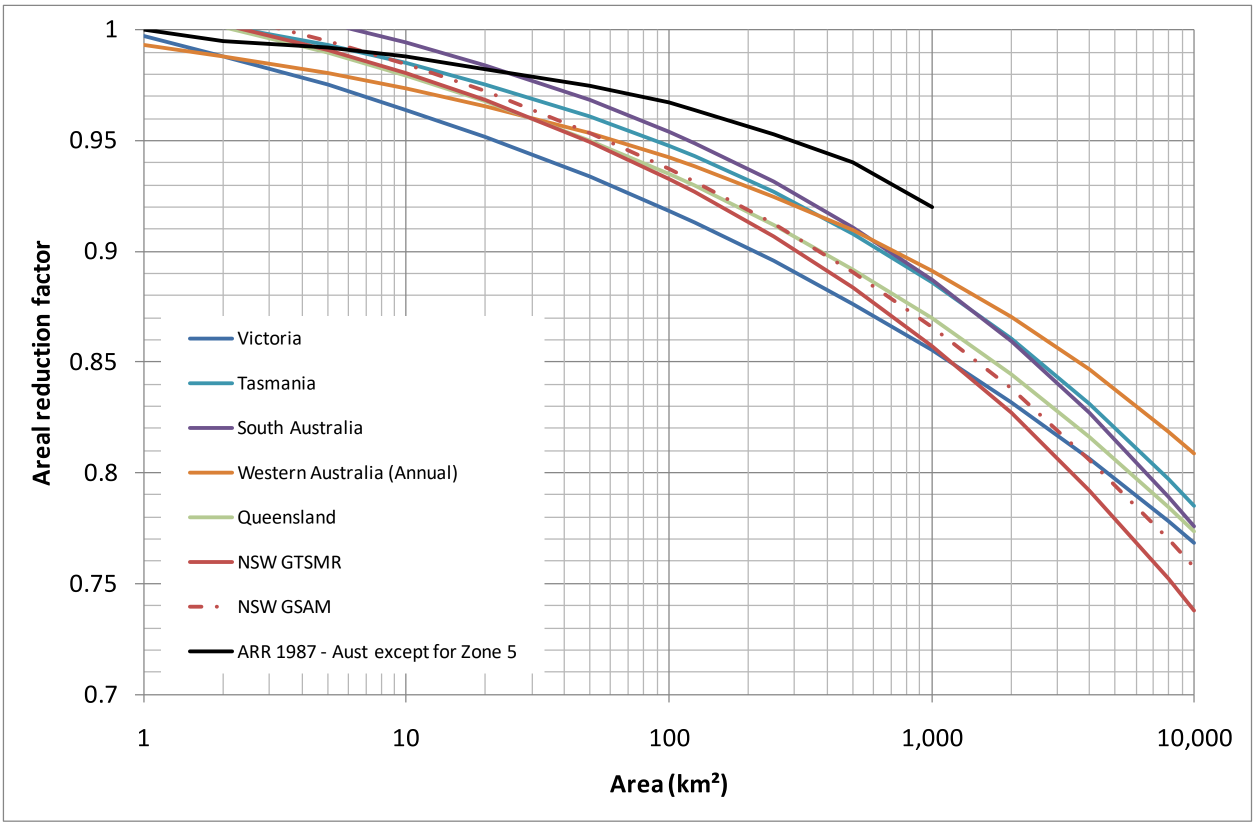

Figure 5-3 ARF curves for all regions for AEP = 0.5 for 24 hour duration

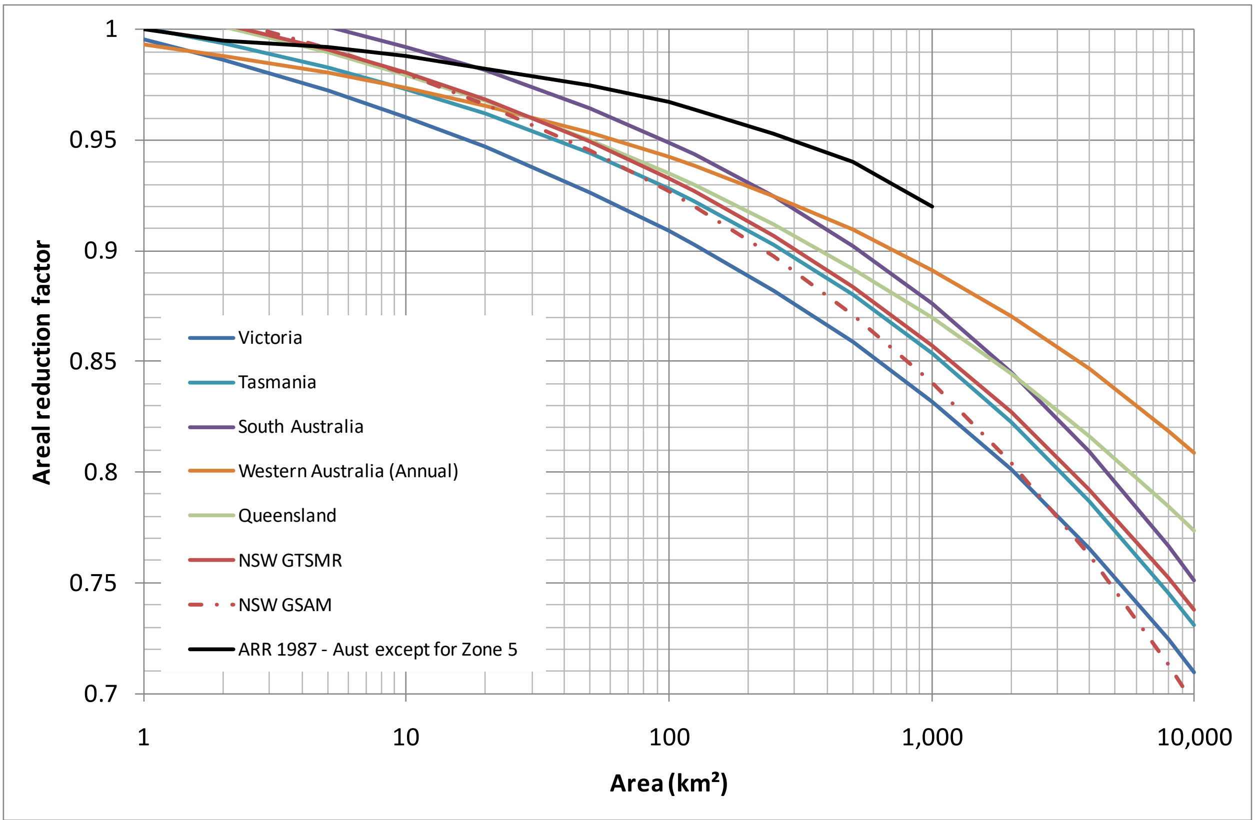

Figure 5-4 ARF curves for all regions for AEP = 0.0005 for 24 hour duration

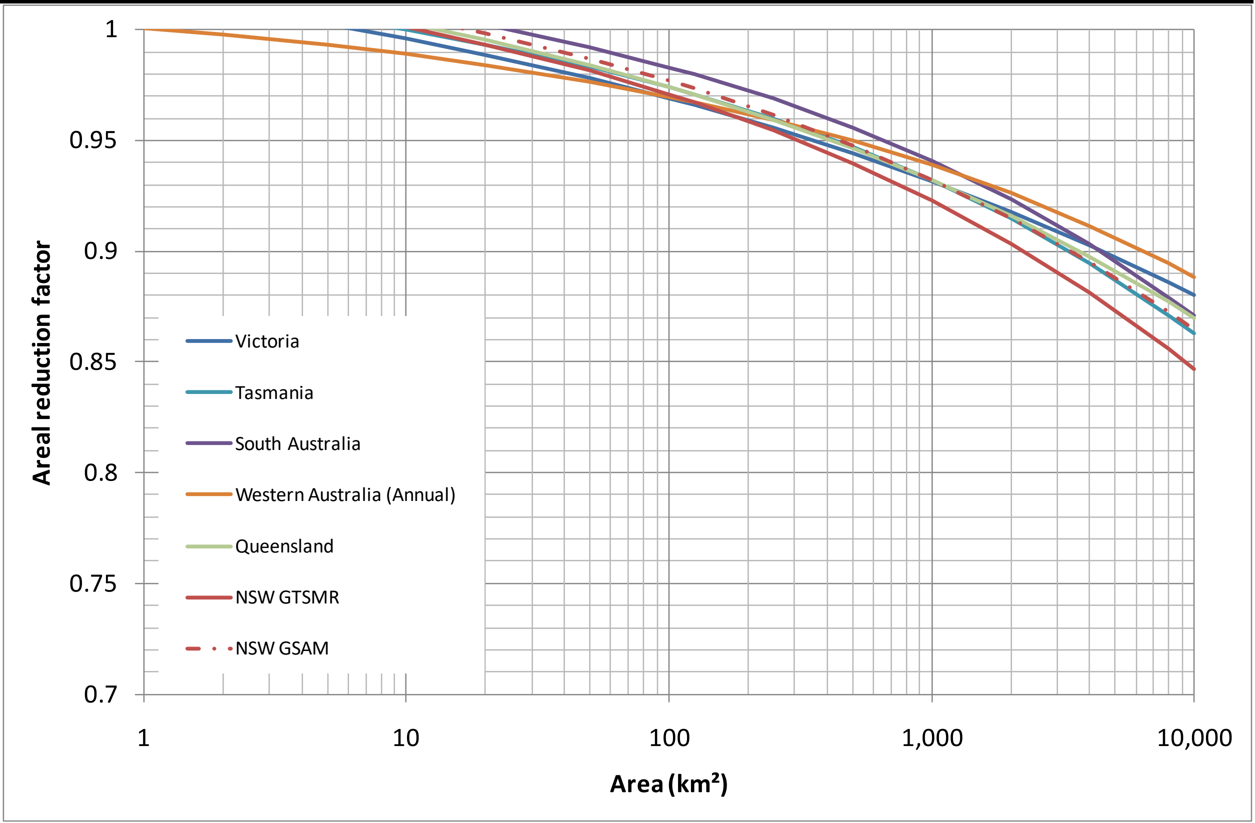

Figure 5-5 ARF curves for all regions for AEP = 0.5 for 72 hour duration

The earliest and latest of the CRC FORGE projects completed were Victoria and New South Wales and ACT, which respectively used daily rainfall data up to the end of 1996 and 2008. While it is possible that there may be some influence of climatic variability or climate change on ARFs, it is difficult given our current understanding of the hydrometeorology that drives variations in ARF to infer this. It is unlikely that there would be any appreciable change introduced in ARFs by only extending the analysis with the additional 4 to 16 years of data (depending upon the region) collected since the completion of the CRC FORGE projects.

5.2. Recommendations on use of areal reduction factors in Australia

Considerable progress has been made on the derivation of ARFs using Australian data since the 1987 edition of Australian Rainfall and Runoff . Projects undertaken in each of the Australian states and the ACT to produce the CRC-FORGE estimates of design rainfall also produced equations for ARFs that are applicable for long durations (18 to 120 hours) and for catchment areas between 1 and 10,000 km² and AEPs between 0.5 and 0.0005. These locally developed equations have been developed using large databases of daily rainfall data that have been appropriately quality controlled and using consistent applications of Bell's (1976) method. The equations for long durations developed using these CRC-FORGE studies are therefore more applicable to Australia then the equations recommended in Australian Rainfall and Runoff (1987).

It is recommended that the long duration equations derived as part of the CRC-FORGE studies discussed in this report and summarised in Section 4 are adopted for ARFs in Australia. They follow the general form shown below in Equation 1. The parameters in the formulae for each region are detailed in Table 5-1.

No CRC-FORGE project has been undertaken to date for the Northern Territory and as an interim measure it is recommended that the Queensland equation is adopted in the Northern Territory.

$$\begin{aligned} &Areal\ reduction\ factor \\ &\quad = Min\{1, [1 + a(Area^b + c\log_{10} Duration)Duration^d \\ &\quad + eArea^f Duration^g (0.3 + \log_{10} AEP)]\} \end{aligned}$$

Where

Area = Area of interest in km² (between 1 and 10,000 km²)

Duration = Storm duration in hours (between 18 and 120 hours)

AEP = Annual exceedance probability as a fraction between 0.5 and 0.0005

Equation 1

Table 5-1 Parameters for long duration areal reduction factor equations (in the form of Equation 1) for each region

Region	a	b	c	d	e	f	g
Victoria	-0.4	0.14	-0.7	-0.48	0.0002	0.4	0.41
Tasmania	-0.105	0.216	-0.882	-0.343	0.0012	0.223	0.335
South Australia	-0.14	0.22	-1.09	-0.42	0.0001	0.35	0.5
Western Australia Annual	-0.13	0.21	-0.56	-0.45	0	-	-
Queensland	-0.2257	0.1685	-0.8306	-0.3994	0	-	-
New South Wales GSAM (including ACT)	-0.23	0.183	-0.91	-0.43	0.00048	0.38	0.21
New South Wales GTSMR	-0.19	0.2	-0.87	-0.412	0	-	-
Northern Territory	As interim measure, adopt Queensland parameters						

Western Australia was the only state where parameter sets for the ARF equation were derived for the winter and summer seasons, which were distinct from the parameters applicable for annual curves in Western Australia. The summer season for Western Australia was defined as the months of October to March inclusive. Seasonal ARF parameter sets for Western Australia are as shown in Table 5-2.

Table 5-2 Parameters for long duration areal reduction factor equations (in the form of Equation 1) for two seasons in two regions of Western Australia.

Region	a	b	c	d	e	f	g
Western Australia Winter	-0.11	0.24	-0.3	-0.52	0.0004	0.32	0.38
Western Australia South West Summer	-0.11	0.25	-0.35	-0.48	-0.1408	0.01	-0.52
Rest of Western Australia Summer	-0.23	0.17	-0.57	-0.4	-0.0287	0.21	-0.41

Analysis of ARFs for shorter duration events (less than 18 hour duration) in Australia is considerably less extensive than for long duration events (18 to 120 hour duration). As an interim measure, equations for short duration events have been derived that produce consistency with the long duration ARF equations in each region and that assume the 1 hour duration ARF values derived in the United Kingdom Flood Studies report are also applicable to Australia (Natural Environmental Research Council, 1975). To ensure consistency of ARFs across all durations less than 18 hours for all areas, parameters of the interim short duration curves for some regions were re-derived as part of the current project. The re-derived interim curves resulted in relatively minor differences to the interim curves that were produced by previous authors. While further research work to establish ARFs derived from Australian data would be desirable for short duration events, it is recommended that the adjusted interim ARF equations are adopted for use in Australia until this future research produces an alternative recommended equation. No CRC-FORGE project has been undertaken to date for the Northern Territory and as an interim measure it is recommended that the Queensland equation is adopted in the Northern Territory.

The interim short duration areal reduction factor equations all follow the general form shown below in Equation 2. The parameters in the formulae for each region are detailed in Table 5-2.

$$Areal\ reduction\ factor = Min\left\{1, \left[1 + a\left(Area^{b} + c\right) + d(Area^{e})(f - \log_{10} Duration)\right]\right\}$$

Where

Area = Area of interest in km² (between 1 and 10,000 km²)

Duration = Storm duration in hours (between 1 and 18 hours)

Equation 2

Table 5-3 Parameters for short duration areal reduction factor equations (in the form of Equation 2) for each region

Region	a	b	c	d	e	f
Victoria	-0.1	0.14	-0.879	-0.029	0.233	1.255
Tasmania	-0.0342	0.222	-1.094	-0.0291	0.302	1.29
South Australia	-0.015	0.014	-6.12	-0.05	0.18	2.48
Western Australia	-0.0518	0.257	-0.553	-0.0231	0.333	0.63
Queensland	-0.0539	0.205	-0.925	-0.0246	0.313	1.16
New South Wales – GTSM–R	-0.0449	0.207	-1.032	-0.0258	0.299	1.37
New South Wales – GSAM (including ACT)	-0.0439	0.23	-0.923	-0.0255	0.309	1.17
Northern Territory	As interim measure, adopt Queensland parameters					

The ARF equations are only recommended for use for events with an AEP of 0.0005 or greater (i.e. more common than 1 in 2000). For more extreme events, the procedures recommended in Book VI of Australian Rainfall and Runoff (Nathan and Weinmann, 2000) should be used to determine catchment average design rainfall depths. The interpolation procedure recommended by Nathan and Weinmann (2000) uses the catchment average design rainfall depth for 0.0005 AEP, which would be calculated using the average of the point design intensities across the catchment multiplied by the ARF estimates recommended above and the PMP depth, which is already estimated as a catchment average value.

The largest circular catchments used in the CRC FORGE projects to estimate ARF were 8,000 km² and the recommended range of applicability of the equations was extended to 10,000 km². With caution, it is possible that the equations could be applied to catchments larger than 10,000 km². As the catchment area increases beyond 10,000 km², it becomes increasingly likely that storm events would only influence part of the overall catchment area, which increases the uncertainty associated with adjusting point design intensities using an ARF.

5.3. Recommendations for further research

The CRC-FORGE projects for the different states and the Australian Capital Territory have defined a set of ARF equations for long rainfall durations (18 to 120 hours) that can be applied by practitioners across Australia. However, this ARF development work had been undertaken independently, and no additional work has since been done to analyse and review the results for individual states in a more integrated fashion. There are thus unanswered questions on (i) the extent to which variations in ARF values for different states are statistically significant, and (ii) whether there would be scope for a more rationally based delineation of boundaries between regions than the currently adopted regions based on state boundaries. As an initial step towards the resolution of both these questions, it is recommended that the differences in regional equations be re-examined in the light of the available information on estimation uncertainties. This should assist in the formulation of clearer recommendations for inclusion in ARR (and possibly reduce boundary problems).

To date, no CRC-FORGE project has been conducted in the Northern Territory and as a result, no ARF equations have been derived for this region. It is recommended that a study is undertaken to derive ARFs for the Northern Territory.

By contrast to the detailed development work on ARFs equations for long rainfall durations, ARFs for shorter duration events (less than 18 hours) are "interim" guidance, extrapolated to the 1 hour duration ARF curve from the United Kingdom, and therefore subject to considerably larger uncertainty. To provide more soundly based ARF values for Australian regions, it is strongly recommended that work is undertaken to develop ARF equations for durations less than 18 hours that are fitted to Australian rainfall data. The development of short duration ARF equations should be a more tractable problem to solve now than it was in previous decades, given that there are relatively dense networks of pluviograph gauges around most of the Australian capital cities and in some other regions of the country; and that over the last decade the Bureau of Meteorology has been archiving radar rainfall data and undertaking quality control and calibration of the radar data using pluviographs to potentially make it useful for this purpose. It is recommended that the ARF equations developed for short durations are developed in such a way that there is a relatively smooth transition to the equations that are currently recommended for long durations in each region. As an initial step in this development, it would be desirable to collate and analyse the results of more recent work on short duration ARFs for Australian catchments and to compare these results to the 1 hour duration ARF curve from the United Kingdom.

The ARF equations developed in Australia have been derived using data-driven and empirical methods, with limited theoretical underpinning. ARF values for a particular catchment would derive from a combination of the mixture of storm types causing heavy rainfall within a region, the direction and speed of movement of those storms and the spatial and temporal characteristics of those storms. Analysis by a hydrometeorologist of the prevalence of different storm types within different parts of Australia and the advection, temporal and spatial characteristics of those storms is likely to provide an understanding of the causes of variations in ARF. Such understanding is difficult to infer directly, on its own, from the empirically derived ARF equations that are currently recommended for use in Australia. It is recommended that hydrometeorologists are engaged to investigate the causes of variations in ARF.

Once the hydrometeological analysis recommended above has been undertaken, the outcomes of that work may enable further research and improvements in the following areas:

- It would be of interest to examine how well the ARFs derived using an empirical method such as Bell's method used in this study, compare with those derived from a suitable theoretical method that may better account for hydrometeorological understanding of the drivers of variability in ARFs.
- There are some areas within each of the regions where the ARF values determined empirically for the circular catchments demonstrated a trend toward being larger or smaller than the fitted ARF equations, which were fitted to the mean ARF values from all circular

catchments within the region for a given area, duration and AEP. Hydrometeorological understanding may enable definition of smaller sub-regions, combining of existing regions (with the existing regions largely defined using state and territory boundaries), or definition of new regions in order to reduce the uncertainty introduced by this variability.

- Seasonality was found to be a significant driver of ARFs in Western Australia but has not been investigated for other parts of Australia. Hydrometeorological understanding may guide the regions where seasonal dependence in ARF would be likely, the start and end dates of seasons and how transition periods between seasons should be handled.
- Climatic variability at inter-decadal scales is likely to influence the relative occurrence and severity of different types of heavy rainfall events. Hydrometeorological understanding of the connection between storm types and ARFs may enable definition of ARFs that are connected to variations in long-term climate drivers in at least some regions.
- Similarly, climate change induced by anthropogenic green house gas emissions is likely to influence the relative occurrence and severity of different types of heavy rainfall events over coming decades. Hydrometeorological understanding of the connection between storm types and ARFs may enable predictions of the future trend in ARFs that will occur as the climate changes over coming decades.

It is recommended that after an appropriate study has been undertaken to determine the hydrometeorological causes of variations in ARF that further studies are then scoped and prioritised according to areas where the hydrometeorological causes are best exploited to reduce residual uncertainty in ARFs.

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Appendix A **Refitting of Interim Areal Reduction Factor Equations for Short Duration (1 to 12 hour) Rainfall Events for Queensland, Western Australia, New South Wales and the Australian Capital Territory**

Analysis of ARFs for shorter duration events (less than 18 hour duration) in Australia is considerably less extensive than for long duration events (18 to 120 hour duration). As an interim measure, equations for short duration events have been derived that produce consistency with the long duration ARF equations in each region and that assume the 1 hour duration ARF values derived in the United Kingdom Flood Studies report are also applicable to Australia (Natural Environmental Research Council, 1975). To ensure consistency of ARFs across all durations less than 18 hours for all areas, parameters of the interim short duration curves for some regions were re-derived as part of the current project. The re-derived interim curves resulted in relatively minor differences to the interim curves that were produced by previous authors.

Interim curves for short duration events were derived by Sinclair Knight Merz (2010) for New South Wales and the Australian Capital Territory, by Sinclair Knight Merz (2012) for Western Australia and by Jordan (2012) for Queensland. Figure A- 1 shows that there is an inconsistency, for catchment areas less than 10 km^2, between the interim curve for 12 hour duration derived by Jordan (2012) and the 18 hour duration curve from Hargraves (2005), with the curves crossing over one another. Similar problems occur between the long duration and the interim short duration curves for Western Australia and for New South Wales and the Australian Capital Territory.

Gamble *et al.* (1998) had proposed the adoption of the same interim short duration equations as were derived for Victoria by Siriwardena and Weinmann (1996a). However, this resulted in a larger separation between the interim short duration curve and the long duration curve for Tasmania than is plausible.

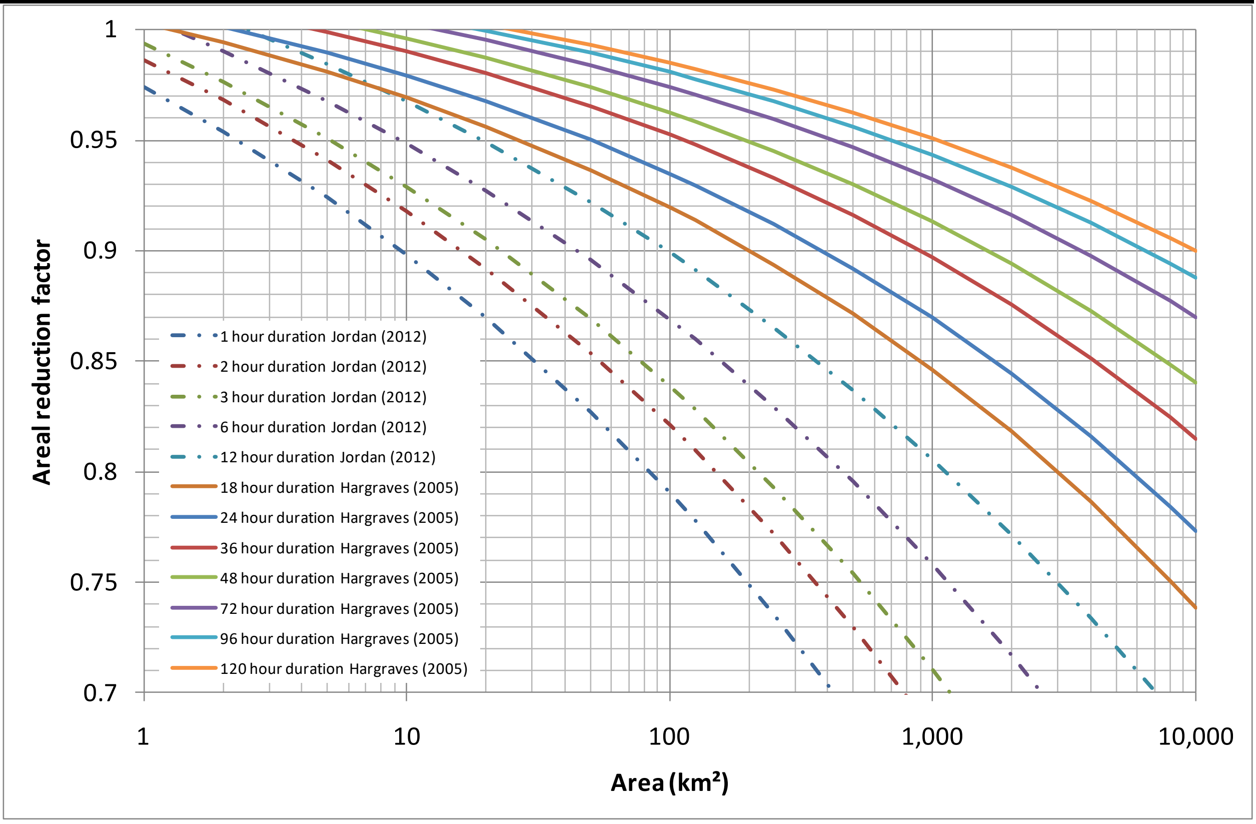

Figure A- 1 Long duration ARF curves for Queensland derived by Hargraves (2005) and interim short duration ARF curves for Queensland derived by Jordan (2012), demonstrating the inconsistency between the curves for 12 and 18 hour durations for smaller catchment areas

This appendix explains re-derivation of interim short duration ARF equations for Queensland, New South Wales, ACT, Tasmania and Western Australia that avoid inconsistency between the interim short duration and long duration ARF curves in each region.

An equation with the functional form shown in Equation 23 was derived for each region. The parameters of the interim short duration equation for each region were fitted to:

- Minimise the sum of square of the differences between the interim fitted equation and the ARF values for 1 hour duration from the *United Kingdom Flood Studies Report* (Natural Environmental Research Council, 1975) for catchment areas of 1, 5, 10, 25, 50, 100 and 250 km^2; and
- Minimise the sum of square of the differences between the interim fitted equation and the ARF values for 18 hour duration derived from the long duration equation each region for catchment areas of 1, 2.5, 5, 10, 25, 50, 100, 250, 500, 1000, 2500, 5000 and 10,000 km^2; whilst
- Avoiding sets of parameter values that cause the interim equation for 12 hour duration to produce an ARF value for a particular catchment area that exceeds the ARF value for an 18 hour event estimated from the long duration equation for the same catchment area.

Figures A-2 to A-6 (below) demonstrate that, consistently for all regions:

- The revised 12 hour duration curve no longer crosses the 18 hour curve fitted to long duration data for the corresponding region;

- The revised 1 hour duration curve fits well to the ARF values for 1 hour duration from the *United Kingdom Flood Studies Report* (Natural Environmental Research Council, 1975) for catchment areas between 1 and 250 km^2;
- The revised 18 hour duration curve fits well to the 18 hour curve fitted to long duration data for the corresponding region for catchment areas between 1 and 10,000 km^2; and
- The difference between the revised interim short duration ARF equation curve and the interim short duration ARF curve that had been fitted in previous publications for the corresponding region, for the same combination of catchment area and event duration, differ by less than 0.01 across most of the range of durations and catchment areas shown; but
- The exception is Tasmania, where larger differences (up to 0.05) were found between the revised interim short duration ARF equation and the interim short duration ARF from Siriwardena and Weinmann (1996a) that had previously been recommended for use in Tasmania by Gamble *et al.* (1998).

Queensland

The revised short duration ARF equation for Queensland is given by

$$ARF = Min\{1, [1 - 0.0539(Area^{0.205} - 0.925) - 0.0246(Area^{0.313})(1.16 - \log_{10} Duration)]\}$$

Equation 14

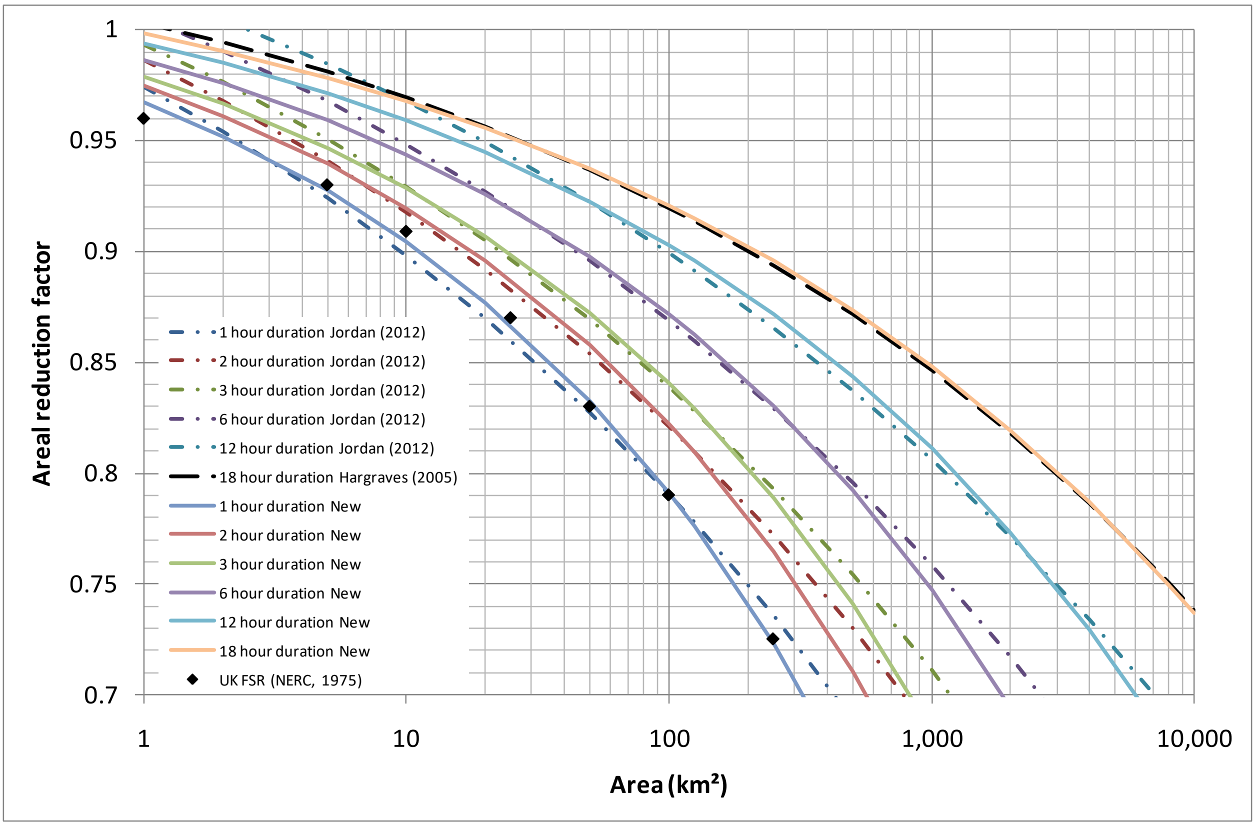

Figure A- 2 Revised short duration ARF curves derived for Queensland, compared to the 18 hour duration ARF curve for Queensland from Hargraves (2005), the 1 hour ARF values from Natural Environmental Research Council (1975) and the interim short duration ARF curves derived for Queensland by Jordan (2012)

Western Australia

The revised short duration ARF equation for Western Australia is given by

$$ARF = Min\{1, [1 - 0.0518(Area^{0.257} - 0.553) - 0.0231(Area^{0.333})(0.63 - \log_{10} Duration)]\}$$

Equation 9

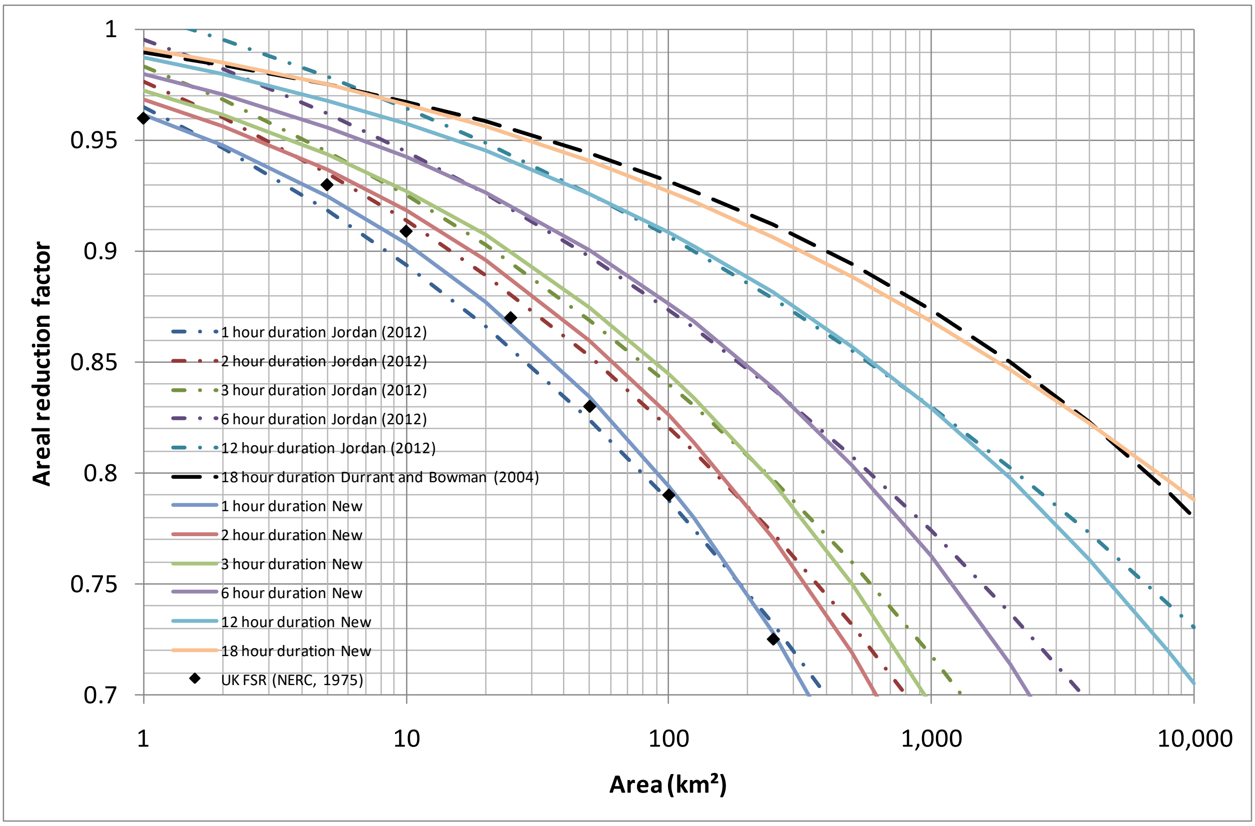

Figure A- 3 Revised short duration ARF curves derived for Western Australia, compared to the 18 hour duration ARF curve for Western Australia from Durrant and Bowman (2004), the 1 hour ARF values from Natural Environmental Research Council (1975) and the interim short duration ARF curves derived for Western Australia by Sinclair Knight Merz (2012)

New South Wales and Australian Capital Territory GSAM Region

The revised short duration ARF equation for the GSAM Region of New South Wales and the Australian Capital Territory is given by

$$ARF = Min\{1, [1 - 0.0439(Area^{0.23} - 0.923) - 0.0255(Area^{0.309})(1.17 - \log_{10} Duration)]\}$$

Equation 17

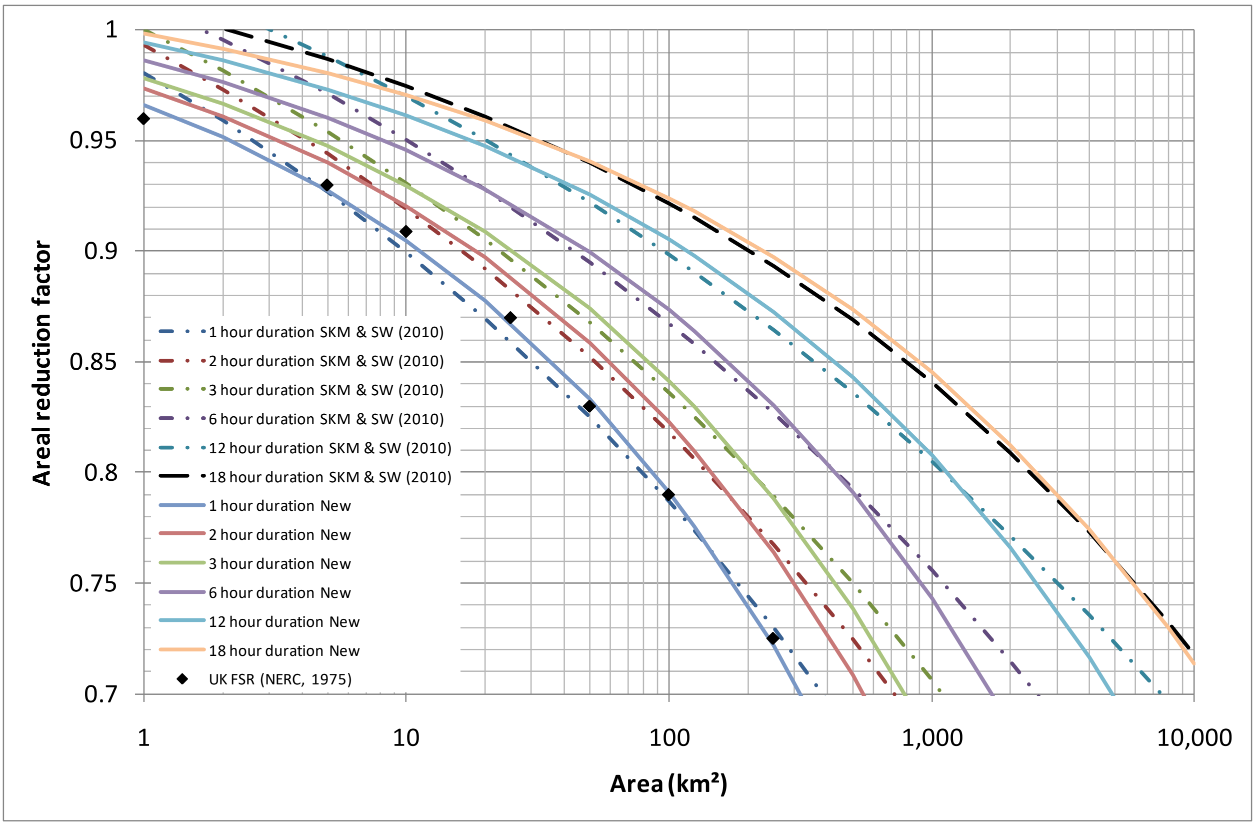

Figure A- 4 Revised short duration ARF curves derived for the GSAM region of NSW and the ACT, compared to the 18 hour duration ARF curve for the GSAM region of NSW and the ACT from Sinclair Knight Merz and State Water (2010), the 1 hour ARF values from Natural Environmental Research Council (1975) and the interim short duration ARF curves derived for the GSAM region of NSW and the ACT by Sinclair Knight Merz and State Water (2010)

New South Wales GTSM-R Region

The revised short duration ARF equation for the GTSM-R Region of New South Wales is given by

$$ARF = Min\{1, [1 - 0.0449(Area^{0.207} - 1.032) - 0.0258(Area^{0.299})(1.37 - \log_{10} Duration)]\}$$

Equation 18

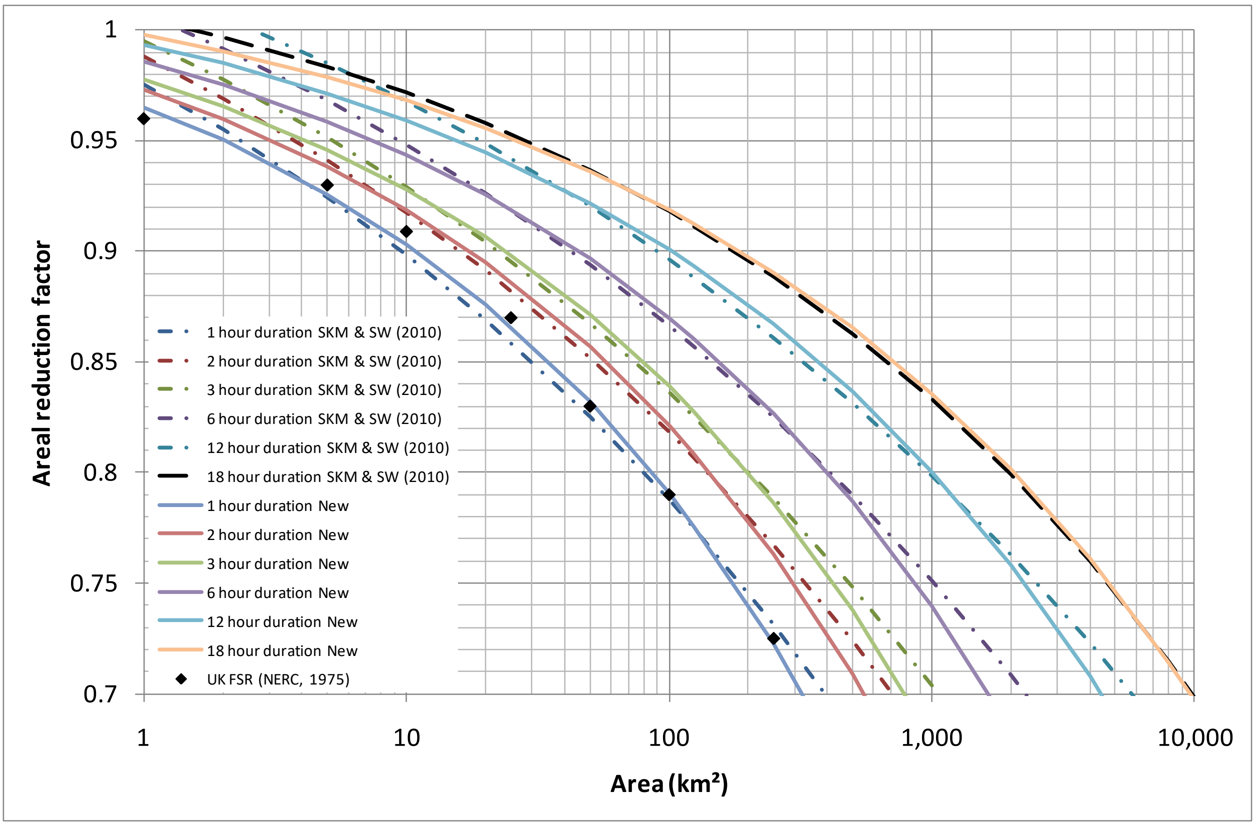

Figure A- 5 Revised short duration ARF curves derived for the GTSM-R region of NSW, compared to the 18 hour duration ARF curve for the GTSM-R region of NSW from Sinclair Knight Merz and State Water (2010), the 1 hour ARF values from Natural Environmental Research Council (1975) and the interim short duration ARF curves derived for the GTSM-R region of NSW by Sinclair Knight Merz and State Water (2010)

Tasmania

The revised short duration ARF equation for Tasmania is given by

$$ARF = Min\{1, [1 - 0.0342(Area^{0.222} - 1.094) - 0.0291(Area^{0.302})(1.29 - \log_{10} Duration)]\}$$

Equation 6

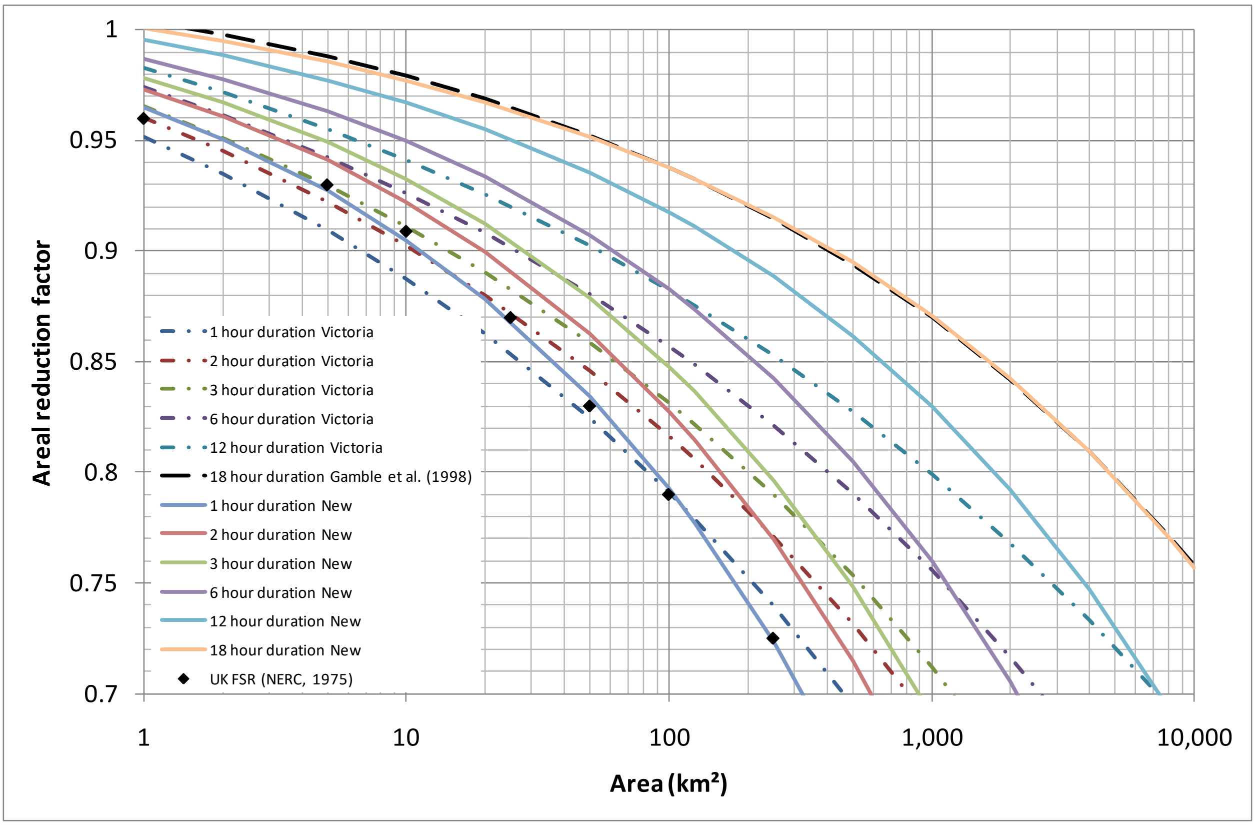

Figure A- 6 Revised short duration ARF curves derived for Tasmania, compared to the 18 hour duration ARF curve for Tasmania from Gamble *et al.* (1998), the 1 hour ARF values from Natural Environmental Research Council (1975) and the interim short duration ARF curves from Siriwardena and Weinmann (1996a) that had previously been recommended for use in Tasmania by Gamble *et al.* (1998)

Summary

The table below summarises the parameters of the interim short duration areal reduction factor equations that were derived in this appendix for Queensland, Western Australia, Tasmania New South Wales and the Australian Capital Territory.

Table A-1 Parameters for interim short duration areal reduction factor equations (in the form of Equation 23) for regions that are discussed in Appendix A

Region	a	b	c	d	e	f
Tasmania	-0.0342	0.222	-1.094	-0.0291	0.302	1.29
Queensland	-0.0539	0.205	-0.925	-0.0246	0.313	1.16
Western Australia	-0.0518	0.257	-0.553	-0.0231	0.333	0.63
New South Wales – GTSM–R	-0.0449	0.207	-1.032	-0.0258	0.299	1.37
New South Wales – GSAM (including ACT)	-0.0439	0.23	-0.923	-0.0255	0.309	1.17