DERIVATION OF AREAL REDUCTION FACTORS FOR DESIGN RAINFALLS IN VICTORIA

For Rainfall Durations 18 – 120 hours

L. Siriwardena
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Report 96/4
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PREFACE

The work presented in this report addresses an important gap in Australian design flood estimation practice: the conversion of point estimates of design rainfall into average rainfall estimates over a catchment, using *areal reduction factors*. The previously used factors were based on overseas data, and recent studies have shown them to be of only limited relevance to Australian conditions.

This report, one of the outcomes from CRC Project D3 "Probability and Risk of Extreme Floods", outlines the methodology adopted to derive design values of areal reduction factors for catchments in Victoria, for rainfall durations from 18 to 120 hours, and for catchment sizes from 1 to 10,000 km^2. Of particular importance are the results of research into the variation of areal reduction factors with the annual exceedance probability (AEP) of rainfall, allowing the determination of areal reduction factors for extreme rainfalls, to a lower AEP limit of 1 in 2000.

As the areal reduction factors derived in this project are directly based on the analysis of Victorian rainfall data, they are considered to be superior to the currently used values, and are recommended for adoption in future design flood studies for Victorian catchments.

Russell Mein
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ABSTRACT

Design rainfall information for flood estimation is generally made available to designers in the form of *point rainfall intensities*. 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 over the whole of the catchment area.

ARF values for a catchment of a given size can be determined from separate frequency analyses of extreme values of point rainfall and areal rainfall for selected durations. The determination of average ARF values for a whole region requires the repetition of this procedure for many different "sample catchments" of that size. The ARF values presented in this report are based on a detailed study using daily rainfall data from over 2000 rain gauges in Victoria. The methodology used is a modified version of Bell's method (Bell, 1976) and was selected on the basis of an extensive literature survey (Srikanthan, 1995). The adoptation of the final method described in this report followed extensive evaluation of variations in procedural steps, as detailed in Siriwardena and Weinmann (1996).

Individual ARF values were computed for a large number of circular "sample catchments" distributed over those parts of Victoria with a relatively high rain gauge density. Sets of ARF values were derived for rainfall durations of 1, 2 and 3 days, catchment areas of 125, 250, 500, 1000, 2000, 4000 and 8000 km^2, and for AEPs of 1 in 2, 5, 10, 20, 50 and 100. A sample mean value of ARF was then determined for each combination of catchment area, rainfall duration and AEP, and a single equation was fitted to these mean values to represent the dependence of ARF values on these characteristics.

The study identified small but statistically significant differences in ARF values for different parts of Victoria, probably reflecting differences in hydrometeorological factors such as dominant storm types. However, there is at present insufficient information to allow differentiation of design values within Victoria based on catchment location. The application of a single set of design ARF values over the whole of Victoria is therefore recommended at this stage.

The design relationship established in this study allows determination of areal reduction factors in Victoria for a range of catchment areas from 1 to 10,000 km^2, rainfall durations from 18 to 120 hours and AEPs from 1 in 2 to 1 in 2000.

It was shown that the ARFs derived in this study are significantly lower than the values given in Australian Rainfall and Runoff (IEAust, 1987). This study also confirmed a tendency for ARF values to decrease with AEP. It is recommended that the ARF values derived in this study replace the values in Australian Rainfall and Runoff for design flood studies of catchments in Victoria and regions with similar hydrometeorological characteristics.

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1. INTRODUCTION

1.1 Background

Design rainfall information for flood estimation is generally made available to designers in the form of *point rainfall intensities* (eg. the rainfall intensity-frequency-duration information given in "Australian Rainfall and Runoff", I. E. Aust., 1987). 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 average recurrence interval (ARI), 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 over the whole of the catchment area.

Due to a lack of adequate research carried out in Australia to derive areal reduction factors for use in the different parts of the country, "Australian Rainfall and Runoff" (IEAust, 1987) [hereafter referred to as ARR87] recommended the set of curves derived from a study in the Chicago area for all Australian zones except for Zone 5 (Figure 2.6 in ARR87) for any average recurrence interval (ARI) up to 100 years. The areal reduction factors obtained from a study in the Arizona area, a semi-arid part in the United States, were recommended for use in Zone 5.

There has since been a concern in some sections of the hydrological community in Australia that the US results may not be appropriate for the Australian conditions. This concern was confirmed by the recent 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, recent overseas studies (Bell, 1976; Stewart, 1989) have conclusively shown that areal reduction factors are dependent on the average recurrence interval (ARI) of the rainfall. The above investigations have led to the conclusion that the development of areal reduction factors appropriate to Australia is a high priority research area in flood estimation.

The available methods for deriving areal reduction factors can be broadly classified into three categories, namely, empirical, analytical and analytical-empirical methods. Srikanthan (1995) presents a review of the existing methods for deriving areal reduction factors (ARFs) in relation to their theoretical background and reported applications using Australian data.

1.2 Objectives and scope of the study

This report summarises the studies carried out for Sub-project 5 of the CRCCH Project D3, which aimed to provide improved areal reduction factors (ARFs) for catchments in Victoria. A review report by Srikanthan (1995) constituted the first stage of this study. Based on the review of the existing methods available for derivation of areal reduction factors, he recommended the use of Bell's (1976) method for deriving areal reduction factors for those parts of Victoria where sufficient data is available. This is an empirical method, which allows the derivation of areal reduction factors as a function of annual exceedance probability (AEP).

The objective of this study was to determine areal reduction factors for rainfall durations in the range from one to three days and over a range of AEPs, based on the analysis of *daily rainfall data* for the whole State of Victoria using a modified version of Bell's method. The results were to be presented in a suitable format useful to the practitioner, such as a set of curves and mathematical relationships. The study was also to consider the scope for extrapolation of the results to other durations, catchment areas and AEPs.

Areal reduction factors for durations less than 24 hours will need to be derived in a separate study, based on a detailed analysis of Victorian pluviograph data.

1.3 Overview of the report

This report begins with a review of previous studies on empirically derived areal reduction factors. Chapter 3 provides a description of the methodology (a modified Bell's method) adopted for derivation of areal reduction factors. This chapter also includes a brief description of exploratory runs carried out to fine-tune and validate the methodology. Chapter 4 begins with an investigation for regional variability in areal reduction factors. Then the design values of areal reduction factors for Victoria for durations from 18 to 120 hours are presented as a set of fitted curves. Chapter 5 contains a critical review of the results and a comparison with the values given in ARR87 and other studies using Australian and UK data. A brief summary and conclusions from the study are given in Chapter 6.

2. PREVIOUS STUDIES ON EMPIRICALLY DERIVED AREAL REDUCTION FACTORS

2.1 Available methods for deriving areal reduction factors

A review report by Srikanthan (1995) constituted the first phase of Sub-project 5 "Areal Reduction Factors for Victoria" of CRCCH Project D3 "Probability and Risk of Extreme Floods". The aim of the review was to evaluate existing methods, to recommend a procedure for estimating areal reduction factors (ARFs) and to identify research areas.

The review started with a brief discussion of *storm-centred* and *fixed-area* areal reduction factors. As the former type is not relevant to design rainfalls of moderate to large annual exceedance probabilities (AEPs), only the methods available for deriving *fixed-area* ARFs were considered in detail. Srikanthan (1995) broadly classified the available methods for deriving *fixed-area* areal reduction factors into three categories, namely empirical, analytical and analytical-empirical methods.

In empirical methods, recorded rainfall depths at a number of stations within a "catchment" were used to derive the ARFs empirically. Three existing methods under this category, namely the US Weather Bureau method, the UK method and the Bell's method, were described in the report. The first two methods derive a single value of ARF for a given area and duration, while the Bell's method derives the ARF as a function of annual exceedance probability (AEP).

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. Four models, namely, the Roche (1963) method, the Rodriguez-Iturbe and Mejia (1974) method, the Meynink and Brady (1993) method and the statistical derivation of ARF fall under this category. In all the methods, it is assumed that the rainfall process is stationary and isotropic.

Only one method, the Myers and Zehr (1980) method, was classified under the analytical-empirical category. The ARFs 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.

Based on the review of the above methods Srikanthan (1995) recommended the Bell's method for deriving ARFs for those parts of Victoria where sufficient data is available. A brief description of the Bell's method and other empirical methods that have a wider application is given in following sections. In addition, some other relevant methods are briefly described. Reference should be made to Srikanthan (1995) for description of other methods mentioned above.

2.2 Empirical methods for deriving average values of areal reduction factor

2.2.1 US Weather Bureau method

The fixed area ARFs used in the United States were derived originally by the US Weather Bureau (1957), using 10 to 15 years of data from networks covering areas from 250-1000 km^2, mostly located to the east of the Mississippi River. The ARF was derived by dividing the average annual maximum areal rainfall over the years of record by the average annual maximum point rainfall for all stations within the catchment and for all years of the record. Thiessen weights were used to calculate areal rainfall. A year later, data from 13 other networks were judged in agreement with the original curves (US Weather Bureau, 1958). Derivation of the ARF can be expressed by the following equation.

$$\mathrm{ARF_{US}} = \mathrm{N}.\sum_{j=1}^{n}\sum_{i=1}^{N} w_i.R'_{ij} \bigg/ \sum_{j=1}^{n}\sum_{i=1}^{N} R_{ij} \qquad (2.1)$$

where w_i = Thiessen weighting factor for station i
R_{ij} = annual maximum point rainfall of the chosen duration for year j at station i
R'_{ij} = point rainfall for station i on the day the annual maximum areal rainfall occurs in year j
N = number of stations within the area
n = length of record in years

None of the networks had sufficient length of records to evaluate the effect of AEP on the point-area relationship. As regional variations in the ARFs were generally less than five percent, the same set of values was adopted for the whole region.

2.2.2 Flood Studies Report, UK method

In this method (NERC, 1975), areal rainfall is computed to identify the date of the annual maximum event, and the point values on the day the areal rainfall maximum occurs, R'_{ij}, are noted. The maximum point values, R_{ij}, at each station in the same year are also identified. The ratio of R'_{ij} to R_{ij} at each station in the year is found. The grand mean of those ratios over all stations and all years of record is taken as the ARF and is expressed as:

$$\mathrm{ARF_{UK}} = \frac{1}{nN} \cdot \sum_{i=1}^{N} \sum_{j=1}^{n} \left(R'_{ij} / R_{ij} \right) \qquad (2.2)$$

where n = length of record in years
N = number of stations within the area

Based on a nation-wide study of UK rainfall records, the Flood Studies Report (NERC,1975) produced the composite diagram shown in Figure 2.1, giving ARFs for a range of areas and durations for use in the design context. The Flood Studies Report values, although varying with duration and area, are assumed to be approximately invariant with location within the UK and with recurrence interval. The values are assumed to correspond to an average recurrence interval between 2 and 3 years.

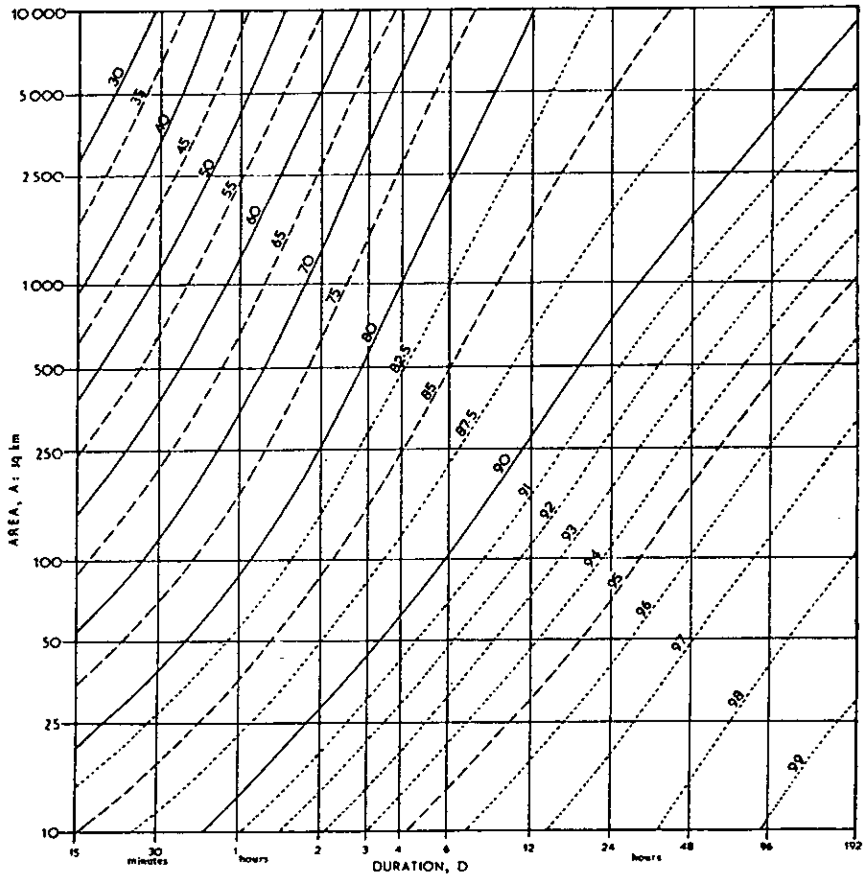


Figure 2.1 : Areal reduction factors from Flood Studies Report (NERC, 1975)

2.3 Empirical methods which account for variation with annual exceedance probability

2.3.1 Bell's method, UK

The concept of Bell's (1976) method was to derive frequency curves of areal and average point rainfall for the catchment of interest and to estimate ARFs by taking the ratio of areal to average point rainfall estimated from the frequency curves at the desired AEPs. The probabilistic interpretation of the ARF in terms of point and areal frequency curves is shown in Figure 2.2. Any tendency for the ARF to vary with annual exceedance probability should be clearly revealed by this method, whereas the other methods (eg. US Weather Bureau, Flood Studies Report) tend to obscure such variations because of their pooling of the data.

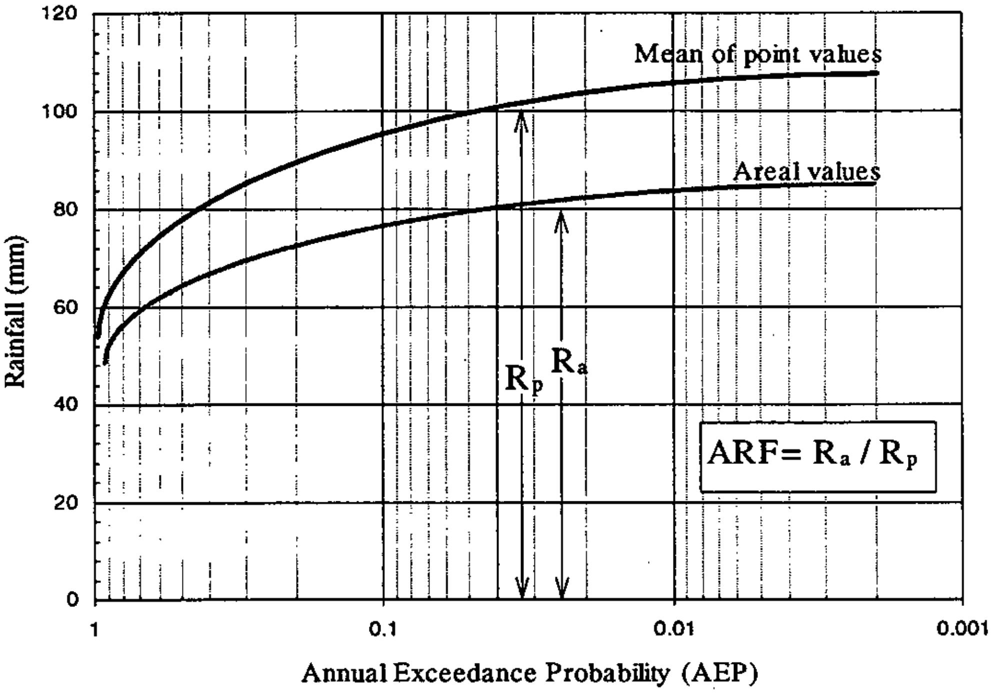


Figure 2.2 : Probabilistic interpretation of areal reduction factor

Bell (1976) used rainfall stations with reasonably complete records over a 14 year period (1961-1974) to calculate ARFs for circular areas of 1000 km^2 in the United Kingdom. A modified Thiessen weighting procedure was used to calculate daily areal rainfall values over the period of record. These were ranked to obtain the 20 independent highest values for each sample area. The areal rainfalls selected by this procedure were regarded as a partial series and were fitted to an exponential distribution with parameters estimated by the method of maximum likelihood.

For derivation of average point rainfall frequency curves, the 20 highest daily rainfalls for every station having a near complete record over the study period were obtained. Instead of deriving separate frequency curves for each station and estimating an approximately weighted average of those curves, a computationally simpler but numerically equivalent procedure was adopted. The weighted average point value was calculated for each rank, the weight being determined by the same modified Thiessen method used for estimating areal rainfalls. Then the ranked average point rainfalls for each area were fitted to an exponential distribution, to obtain estimated average point rainfalls for ARIs from 2 to 20 years. The required values of the ARF were calculated directly from corresponding areal and average point rainfalls for ARIs of 2, 5, 10 and 20 years.

Bell (1976) concluded that there is a statistically significant trend towards lower ARFs with longer average recurrence intervals (ARIs) for both 24-hour and shorter duration rainfalls. The differences were of the order of 2 to 5% between the ARFs of 2 and 20-year ARIs for areas of 1000 km^2 and a duration of 24 hours. He showed that the derived values of ARF reasonably agree with the corresponding values of the Flood Studies Report (NERC,1975) at moderate ARIs, but are significantly lower for high ARIs (20-100 years).

2.3.2 Areal reduction factors by Stewart (1989), UK

Stewart (1989) evaluated ARFs for an area of North West England, in order to investigate their relationships with average recurrence interval (ARI) and location. Analysis of ARFs was undertaken for a range of durations from 1 to 8 days, using 544 square gridded experimental 'catchments', ranging in area from 25 to 10,000 km^2. The analysis of 1, 2, 4 and 8-day rainfall durations was based on 25 years of daily rainfall data from 1961 to 1985.

The methodology used by Stewart (1989) for derivation of ARFs for 1 to 8 days follows that of Bell (1976) with some modifications. Point and areal rainfall frequency curves were derived from annual maximum series, standardised by the mean of annual maxima. At a specified average recurrence interval, T, the ARF can be defined as:

$$\mathrm{ARF(T)} = \mathrm{RC(T)} / \mathrm{RP(T)} \qquad (2.3)$$

where RC and RP denote areal and point rainfalls respectively. If RC_S and RP_S are used to denote standardised areal and point rainfalls, and RC_{BAR} and RP_{BAR} are used to denote the means of annual maximum areal and point rainfalls respectively, then

$$\mathrm{RC_S(T)} = \mathrm{RC(T)} / \mathrm{RC_{BAR}} \qquad (2.4)$$

$$\mathrm{RP_S(T)} = \mathrm{RP(T)} / \mathrm{RP_{BAR}} \qquad (2.5)$$

Hence, ARF can be expressed as :

$$\mathrm{ARF(T)} = \frac{\mathrm{RC_S(T)}}{\mathrm{RP_S(T)}} \cdot \frac{\mathrm{RC_{BAR}}}{\mathrm{RP_{BAR}}} \qquad (2.6)$$

Annual maximum areal rainfall series for each experimental catchment and for each duration were derived. In order to simplify the analysis, the annual maxima for different experimental areas of the same size were pooled after standardising by the mean of annual maxima. A General Extreme Value (GEV) distribution was then fitted by the method of probability weighted moments, following the methodology developed by Hosking et al. (1985). Thus one typical areal rainfall growth curve was derived for each size of experimental area for each duration. Typical n-day point rainfall growth curves for the whole 10,000 km^2 study area were derived in the same way.

Mean values of RC_{BAR} for each size of experimental area, calculated as the mean of annual maximum catchment rainfalls, were applied to the standardised growth curves in order to obtain areal rainfall frequency curves in mm. Similarly, RP_{BAR} was calculated as a weighted average of the gauge mean annual rainfalls over the study area, and used to derive a typical point frequency curve in mm. Areal reduction factors for each duration were then derived directly from the ratio of areal to point rainfall at a given recurrence interval.

Stewart (1989), using daily rainfall data for North West England, confirmed the decrease in the areal reduction factor with recurrence interval; this is in accordance with the results of Bell (1976). She found that the differences were of the order of 1 to 10%, with the rate of decrease in the ARF with ARI increasing as the area increases. The derived values for ARF for North West England were significantly lower than those given in the Flood Studies Report.

2.4 Areal reduction factors for Australia

2.4.1 Recommended values for areal reduction factor in Australian Rainfall and Runoff, 1987

Australian Rainfall and Runoff (IEAust, 1987) notes that there have been few studies of the areal reduction factor appropriate for use in Australia. In the absence of ARFs based on analysis of Australian data, the ARFs derived for certain parts of the United States were considered appropriate for Australian conditions. The ARR87 recommends two sets of ARF curves for Australia, one for coastal and another for inland areas. The set of curves given in Figure 2.3 (Figure 2.6 of ARR87) is based on a study in the Chicago area by the United States National Weather Service (1980). These curves are recommended for use in all climatic zones with the exception of Zone 5 in Figure 3.2 of ARR87. Although the curves are for 2-year average recurrence interval (ARI), they were considered applicable for any ARI up to 100 years. For the use in Zone 5, the ARFs have been obtained from a study in the Arizona area, a semi-arid part of the United States (United States National Weather Service, 1984). These are presented in Figure 2.7 of ARR87.

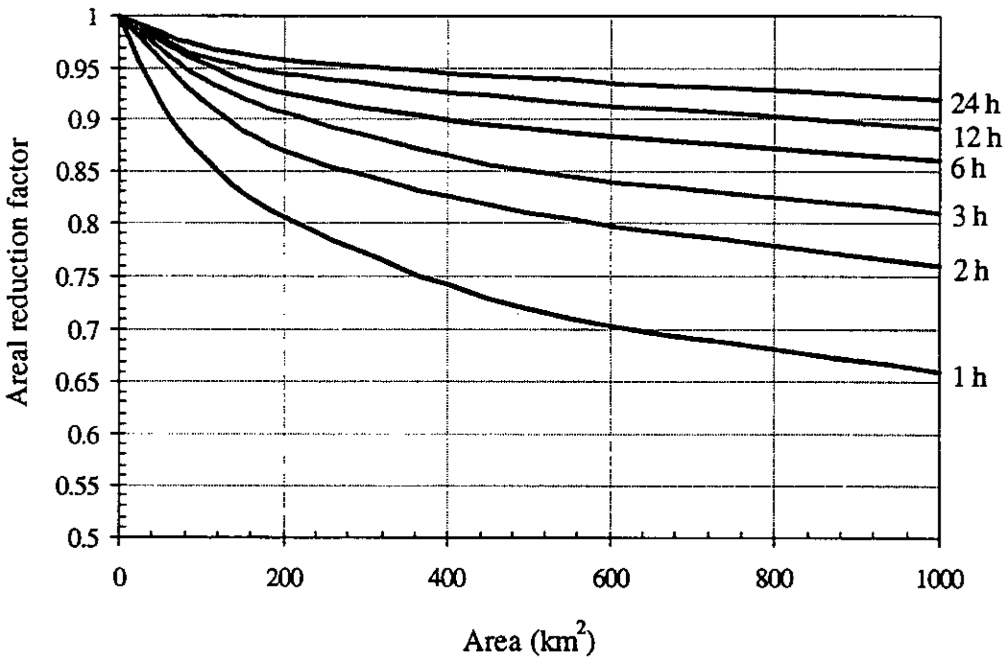


Figure 2.3 : Areal reduction factors for use in Australia (except for Zone 5)
(Figure 2.6 of ARR87, IEAust, 1987)

The ARF values recommended in the ARR87 are based on the application of the method developed by Myers and Zehr (1980), using the rainfall data from the Chicago area (US). The method is classified under the analytical-empirical category, and is based on a computerised model of the structure of annual maximum rain storms and a routine for computing ARFs from these storms. It requires a large amount of data and the process of deriving various statistical surfaces is an extremely time consuming process.

2.4.2 Recent studies in Australia to derive areal reduction factors

In recent times, a number of studies have been carried out in Australia to derive areal reduction factors for different parts of the country, but mainly for the south-eastern coastal region. In general, they fall under fixed-area ARFs based either on empirical or analytical methods. A number of researchers (Avery, 1991; Porter and Ladson, 1993; Nittim, 1989) have used variations of Bell's method to derive ARFs for a range of AEPs and for different durations using daily rainfall data.

In the above methods, the basic procedure used to derive areal reduction factor is :

- Obtain point rainfall estimates at various AEPs from the Intensity-Frequency-Duration (IFD) curves given in Chapter 2 of the ARR87. To account for the areal variability of point rainfall, IFD values are derived at a number of points in the catchment.

- Derive annual maximum areal rainfall series for the desired durations using a suitable weighting procedure (eg. Thiessen weighting factors). The areal rainfall estimates at the desired AEPs are then obtained by fitting a suitable frequency distribution such as a Log-Normal distribution, or a Log-Pearson Type III distribution.
- Convert areal rainfall estimates to 'unrestricted' interval values by applying a suitable factor such as the factors given by Pierrehumbert (1972).
- Obtain an average point rainfall value for the catchment by using a suitable weighting procedure such as Thiessen weights.
- Calculate ARFs by dividing 'unrestricted' areal average rainfalls by the corresponding weighted average of point rainfall values.

Some of the analytical methods used to derive ARFs for different parts of Australia are based on 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 ARFs. Reference should be made to Srikanthan (1995) for a brief description of these methods.

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, the small database used in the above studies precludes any firm quantitative conclusions on appropriate values to replace the ARR87 values and on the dependence of the ARF values on the annual exceedance probability.

2.5 Review of different empirical procedures adopted to derive areal reduction factors

The US Weather Bureau method and the Flood Studies Report method (NERC,1975) obscure the tendency for ARFs to vary with AEP, because of their pooling of the data. Because of the differences in the two methods, they will in general give different estimates for the ARFs. For example, in the US Weather Bureau Method, Thiessen weights are used to obtain areal average rainfall, while an arithmetic average is used for the representative point rainfall. In the UK method, areal rainfall is not directly used in deriving ARFs. Instead, point rainfall ratios are averaged, based on the days of occurrence of the annual maximum point and areal rainfalls.

Bell's method can take into account the variation in the magnitude of ARFs with annual exceedance probability (AEP). Bell fitted an exponential distribution to the partial series of point and areal rainfall in the derivation of ARFs. In variations of the Bell's method, a number of other distributions were used to fit to the annual series of point and areal rainfall. Among those are a Log-Normal distribution (Nittim, 1989; Porter and Ladson, 1993), a Log-Pearson Type III distribution (Avery, 1991) and a GEV distribution (Stewart, 1989). The different distributions may result in different ARF estimates, particularly for the lower AEPs. The distribution which fits the data best needs to be used to obtain the most accurate ARF estimates for a particular region.

Stewart (1989) pooled the data for the whole study area of 10,000 km^2 to obtain a single growth curve for point rainfall by fitting a GEV distribution. Similarly, she derived a single areal rainfall growth curve for each "catchment" size. ARFs were directly estimated from these growth curves (after adjustment for the respective mean values). This procedure obscures the spatial variability when deriving the ARFs for larger areas and emphasises the need for consideration of specific 'catchments' rather than for pooled 'catchments' of the same size. It also needs to ensure that the data are from a hydrologically homogeneous region before pooling.

In some of the variations of the Bell's method used with Australian data (Nittim, 1989; Porter and Ladson, 1993; Avery, 1991), point rainfall values were estimated from the IFD curves given in the ARR87. Since these values have been smoothed for spatial consistency, the resulting ARF values might not be consistent. Moreover, subjectivity in the adjustment to convert areal rainfall amounts from 'restricted' to 'unrestricted' intervals constitutes an other potential source of error.

3 METHODOLOGY FOR DERIVATION OF AREAL REDUCTION FACTORS

In this chapter, a modified Bell's method, the procedure that was used to derive areal reduction factors (ARFs) in this study, is described in detail. The availability of data for deriving ARFs of long durations for Victoria is then discussed. An evaluation of the results of test applications of the proposed methodology, carried out to ascertain that the results would not be unduly affected by variable conditions of data availability, is also included in the later part of this chapter.

3.1 Adopted procedure in deriving areal reduction factors for Victoria (modified Bell's method)

3.1.1 Basis for methodology

The objective of this study was to derive areal reduction factors for Victoria on a regional basis, for durations from 24 to 72 hours. Idealised circular 'catchments' ranging up to an area of 8000 km^2 were employed in the derivation of ARFs, and to investigate their variations with the size of the 'catchment'. To investigate the dependence of the ARF on the annual exceedance probability (AEP), a probabilistic approach to the derivation of ARFs was considered necessary.

Bell (1976) used partial series of areal and point rainfalls over a common base period, having almost complete data records. This enabled the use of observations of equal rank in the computation of ARFs for a selected AEP. In this study, annual maximum areal and point rainfall series for the complete record lengths are used, instead of curtailing records to a common base period. This precludes the use of Bell's method in its original form. The basic modifications needed are the adaptation of the procedure to suit annual series, use of a suitable frequency distribution or plotting position formula to fit the annual series (instead of the exponential distribution used for the partial series), and use of the concept of equal annual exceedance probabilities (AEPs) instead of equal ranks.

Fixed area ARFs are not directly related to the ratios of areal to point rainfall derived from individual storm rainfall amounts. The conceptual significance of the procedure is therefore more statistical than physical. The probabilistic interpretation of ARFs in terms of point and areal frequency curves is shown in Figure 2.2. Here, the fixed area ARF is simply the ratio between the areal and point rainfall amounts with the same annual exceedance probability (AEP).

The basic steps in the derivation of ARFs for each 'sample catchment' are:

- Derive 1, 2 and 3-day annual maximum series of areal rainfall using daily rainfall data.
- Select a suitable frequency distribution (theoretical or empirical) to fit the annual maximum series of areal and point rainfall.
- Estimate the frequency curve of areal rainfall.
- Estimate the representative frequency curve of point rainfall.
- Calculate sample values of the fixed-area ARF as the ratio between the areal and point rainfall estimates corresponding to the same AEP.

ARF values from many samples are then pooled to compute a mean ARF value for each selected combination of rainfall duration, catchment area and AEP.

The computational procedures adopted in these steps are described in Sections 3.1.2 - 3.1.5. The need to analyse data for many catchments covering a range of areas, and the magnitude and nature of the database necessitate massive computational effort, especially for derivation of areal rainfall series from basic data. Hence, a Fortran computer program was developed to facilitate the computation of ARFs from the basic data (see Section 3.1.6).

3.1.2 Derivation of annual maximum areal rainfall series from daily data

Areal rainfall was calculated on a daily basis for each circular 'catchment' using Thiessen weights. All rainfall stations having at least 10 years of daily rainfall data and being located within the catchment or within a distance of about 5 kilometres beyond the catchment boundary were used for computation of Thiessen weights. The computer program can accommodate up to 95 rainfall stations for a catchment. If this limit is exceeded, as could happen for a larger catchment having a dense network of stations, only the 95 stations having the longest records are used. In calculating the areal rainfall on a daily basis, only the stations which have data for that particular day were used to calculate the Thiessen weights. This means that areal rainfalls are based on different combinations of stations, depending on the availability of data. The maximum so determined for the year was taken as the annual maximum areal rainfall. The procedure was repeated for 2-day and 3-day totals.

The accuracy of the estimated areal rainfall depends on the number of stations used to account for the areal variability, and on the spatial correlation structure of the storm. Hence, a minimum number of stations on which the areal rainfall is computed should be defined, depending on the size of the catchment, to safeguard the accuracy of the estimate. The minimum number of stations required to define areal rainfall at any time period was arbitrarily set at three for catchment areas up to 500 km^2, plus one additional station for every 500 km^2 thereafter. For example, for a circular catchment of 2600 km^2, areal rainfall was not calculated during periods for which the number of stations fell below eight. This criterion generally curtails the annual series in the early period of records. Moreover, the accuracy of the derived areal rainfall time series is considered to be higher towards the end of the record period, when the number of stations involved in computation is larger. In some regions, it was difficult to find enough stations having concurrent data for small catchments (eg 100 km^2) to satisfy the above conditions, so that small catchments could only be tested for those regions having a sufficiently dense network of stations.

A computationally simpler approximation to the conventional procedure of Thiessen polygons was used in this study, for ease in computer coding. Grids ranging from 40×40 to 80×80, depending on the size of the catchment, were used to divide the circular catchments into small square elements. Each element located within the catchment boundary was assigned to the nearest rainfall station. Only the stations having data for the particular time period for which weighting factors are sought were considered. Weighting factors were calculated by taking the proportion of elements assigned to each station. Given the uncertainty about the true areal variation of rainfall over the catchment, the errors associated with this approximation were considered negligible.

3.1.3 Adopted frequency distribution and parameter estimation

A theoretical probability distribution (GEV) and an empirical probability distribution (based on the Cunnane plotting positions of the data points) were considered originally for fitting annual maximum areal and point rainfall series. The GEV distribution, being the statistically more robust procedure with respect to sampling variability of the derived ARFs, was adopted in this study. The tests carried out to compare the performance of the two distributions are described in Siriwardena and Weinmann (1996). Salient features of the GEV distribution and procedural steps involved in fitting a GEV procedure using an regional approach are discussed herein.

The three parameter generalised extreme value distribution function can be expressed by:

$$F(x) = \exp\left[-\left\{1-\kappa\left(\frac{x-\xi}{\alpha}\right)\right\}^{\frac{1}{\kappa}}\right] \qquad \alpha > 0 \qquad (3.1)$$

$$\xi+\frac{\alpha}{\kappa} \le x \le \infty \qquad \text{if } \kappa<0$$

$$-\infty \le x \le \xi+\frac{\alpha}{\kappa} \qquad \text{if } \kappa>0$$

Here ξ, α and κ are location, scale and shape parameters respectively.

The GEV distribution was fitted by linear combinations of probability-weighted moments (L-moments). This fitting procedure is considered to be robust and efficient and has been shown to suffer less from the effects of sampling variability and data outliers (Hosking et. al, 1985; Hosking, 1990).

For annual maximum areal rainfall, the parameters of the distribution were estimated from a single series. However, for point rainfall, one frequency curve condensing information from all point rainfall series within the catchment is required. For this purpose a regional procedure of fitting a GEV distribution using L-moments was applied; here the 'region' refers to the circular catchment under study. In brief, the procedure for regional analysis involves the following steps (Cunnane, 1989; Appendices 4 and 5):

- Maximum annual rainfall data at each station are standardised them by dividing by the mean of the annual maxima (standardising value) at that station.
- The first three L-moments are calculated for each standardised rainfall series having at least 30 years of data;
- Weighted averages of all required L-moments are calculated (each station's contribution to the regional average is weighted in proportion to its record length by the factor N_i/L, where N_i is the length of record for station for site i, and L is the sum of all N_i);
- A GEV distribution is fitted to the regional L-moments by the method of probability weighted moments (PWM);
- Quantile estimates of regional standardised rainfall (growth factors) are calculated using the selected distribution;
- Quantile estimates for any specific site are estimated by multiplying the standardised rainfall quantiles by the standardising value for the site.

The assumptions of this regional procedure include the following :

- Rainfall distributions at different stations are identical apart from a scale factor;
- Annual rainfalls are serially independent.

Frequency analysis based on a partial series is considered to give more accurate quantile estimates than with an annual series for AEPs greater than 1 in 10. Langbein (1949), using a theoretical relationship between probabilities for both series, showed that the agreement between the two series is acceptable for AEPs less than 1 in 10. This relationship indicates that a small correction is required to the quantile estimates for AEPs greater than 1 in 10, if they are estimated from an annual series (Fig. 10.2 of ARR87). Considering the fact that the same correction factor is involved with both quantile estimates of areal and point rainfall, the use of annual series in derivation of ARFs for AEPs greater than 1 in 10 is considered to be appropriate.

3.1.4 Quantile estimates for areal and point rainfall

Areal rainfall series

After discarding the years with inadequate data (Section 3.1.2), the resulting annual series was fitted to a GEV distribution to obtain estimates of areal rainfalls at desired probabilities (ie. AEP of 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01), subject to the following constraints :

- If the series contained less than 30 years of data, no estimates were calculated.
- If the series contained less than 50 years of data, the estimate for an AEP of 0.01 (ARI=100 years) was discarded.

These constraints were imposed to safeguard the accuracy of the estimates.

Representative point rainfall series

As a number of rainfall stations are involved with a sample catchment, representative point rainfall quantile estimates were obtained by the regional procedure of fitting a GEV distribution. Regional average parameters, derived from the L-moment analysis of the standardised point rainfall series at individual stations, were used to fit the GEV distribution and to obtain regional growth factors for point rainfall, as described in Section 3.1.3. For the selected AEPs, representative point rainfall estimates for the catchment were then obtained by multiplying the corresponding growth factors by the Thiessen-weighted mean of the standardising values at individual stations. Only stations having annual maximum point rainfalls for at least 30 complete years were used in the analysis.

The above procedure was carried out for rainfall durations of 1, 2 and 3 days.

3.1.5 Derivation of areal reduction factors

Once the areal and point rainfall estimates for the desired AEPs have been estimated by frequency analysis for a sample catchment, ARFs can simply be calculated by dividing areal rainfall estimates by the corresponding point rainfall estimates. The values computed for durations of 1, 2 and 3 days can also be used directly for 'unrestricted' durations of 24, 48 and 72 hours, based on the assumption that correction factors involved in converting rainfall amounts pertinent to 'restricted' durations to 'unrestricted' durations are the same for both areal and point rainfall.

Dwyer and Reed (1995), when analysing a catchment covering an area of 185 km^2 in North Wales, found that areal rainfall renders a correction factor 1.19 as compared to 1.17 for point rainfall. In explaining this result they suggested that the areal rainfall might be expected to require a higher correction factor than point rainfall on the reasoning that the areal rainfall necessarily inherits a smoothing effect. In contradiction, in terms of a fractal analysis of variables, they indicated that areal rainfall may require a lower correction factor than point rainfall if areal and point rainfalls are considered as separate climatic variables. They deduced that an extensive investigation would be required before any firm conclusion would be drawn.

In this study, it was considered that, in the absence of clear evidence for disparity, the same factor is applicable to both areal and point rainfall.

3.1.6 Computer programs

To facilitate computation, a Fortran program was developed to run on a Unix workstation. The basic input to the program is a file containing radius and latitude/longitude of the centres of the circular catchments to be analysed. The program searches through a database file to select all daily rainfall stations which fall within the catchment area and a user-specified distance beyond the catchment boundary (2-5 km). The daily rainfall data files having at least 10 years of data and the annual maximum data files for the selected stations are then copied from the directories where they are stored to the working directory used by the program. The program can accommodate up to 95 rainfall stations for a catchment.

The program gives a graphical display of the ‘catchment’ and the relative positions of the rainfall stations, together with a legend (colour codes) to indicate the length of record. This enables catchments to be selected which have a reasonably uniform distribution of rainfall stations.

The computation of ARFs was based on the methodology described in Sections 3.1.2 to 3.1.5. In the regional procedure for fitting a GEV distribution using L-moments, the computer program developed by Hosking (1990) was adopted as a subroutine. The procedure used in computer coding of Thiessen weights is described in Section 3.1.2.

The derivation of the annual maximum series of areal rainfall takes the most computational time, as this has to be carried out on a daily basis, with a large number of Thiessen weight combinations. A computer run for a catchment with 90 stations may take about 10 minutes.

The program generates both a summary and detailed output files. The summary file contains the derived ARFs for a sample catchment for durations 1 to 3 days, and for a range of AEPs from 0.50 to 0.01. In addition, the detailed output file provides quantile estimates of areal and representative point rainfall for each circular area considered.

3.2 Availability and preparation of data for application

3.2.1 Data used in the study

As this study is concerned with deriving areal reduction factors for longer durations (one to three days), the basic data needed are daily rainfall data for the whole State of Victoria. During a preliminary stage of Project D3, a daily rainfall database for Victoria was established with the support of the Bureau of Meteorology (BoM), Melbourne Regional Office. This database includes rainfall records at more than 2000 stations and the data are compiled in a format suitable for computer applications. In a subsequent study, annual maximum rainfall series for durations up to five days were extracted (Nandakumar and Siriwardena, 1994). Hence, the basic inputs for derivation of ARFs used in this study are :

- Daily rainfall data at more than 2000 stations in Victoria.
- 1, 2 and 3-day annual maximum rainfalls extracted for the above stations.

Daily rainfall data are needed to derive values of annual maximum areal rainfall on a catchment basis. Although stations with short records of data (eg. less than 20 years) are not suitable for frequency analyses, they are useful in improving the estimates of areal rainfall. In order to maximise the use of available information, accumulated daily rainfall totals were disaggregated using the time pattern observed at the nearby stations (see Section 3.2.2).

The rainfall stations having more than 30 years of data are shown in Figure 3.1. As indicated by this map, it may not be possible to derive accurate ARFs for the parts of the State having a sparse network of rainfall stations. These areas may include north-western Victoria and the mountainous regions of east-central Victoria. The north-eastern suburbs of Melbourne have the densest network of rainfall stations.

The number of daily rainfall stations in operation steadily increased up to the year 1915 and then fluctuated until late 1970s when it started to decline.

3.2.2 Disaggregation of accumulated data

As the accumulated rainfall totals over a period of two to several days contain valuable information, it is desirable to disaggregate them for use in this study. A limited extent of disaggregation was carried out during extraction of the one to five day annual maximum rainfalls (Nandakumar and Siriwardena, 1994). Only the accumulated data, which were decisive in the determination of annual maxima, were disaggregated at that stage of the study. The methodology adopted was to graphically display the hyetograph of daily rainfalls at nearby stations for which daily records are complete, and to prompt the user to select one station hyetograph as the basis for disaggregation. As the time required for this procedure is

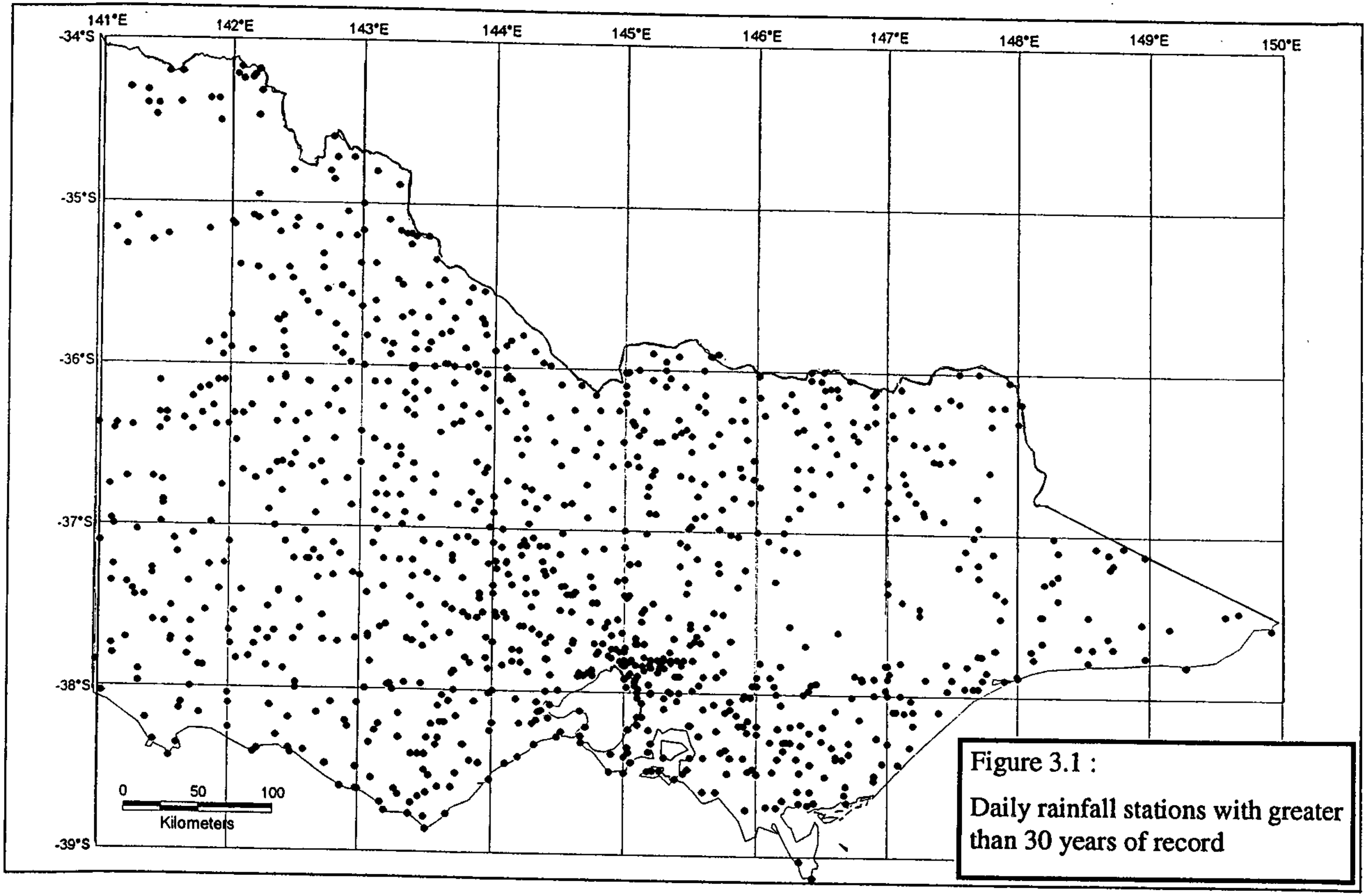


Figure 3.1 :

Daily rainfall stations with greater than 30 years of record fairly large, an automated procedure (with minimal input from the user) was developed for the disaggregation of the remaining accumulated data. However, checks may be needed to guarantee the reliability of such an automated procedure (eg. time shifts in records).

Disaggregation of accumulated totals can be treated mathematically in a variety of ways. The simplest is to use the proportions indicated by the hyetograph at the nearest reference gauge. The limitation of this procedure is that any error in the data of the reference gauge directly affects the results. A more logical approach, proposed by Porter and Ladson (1993), assumes the influence of nearby groups is inversely proportional to their distance from the gauge for which accumulated data is to be distributed. This also safeguards against the uncertainty involved in using data from a single station. If a gauge S has rainfall accumulated over m days and complete data is available from n gauges nearby, on day j the precipitation at gauge S is given by:

$$P_{js} = \frac{\sum_{j=1}^{m} P_{js} \sum_{k=1}^{n} \left\{ p_{jk} / d_k \right\}}{\sum_{k=1}^{n} \left\{ 1 / d_k \right\}} \qquad (3.2)$$

where $\sum_{j=1}^{m} P_{js}$ = precipitation at the subject gauge accumulated over m days

d_k = distance from gauge k to the subject gauge S

p_{jk} = proportion of rainfall on day j to the accumulated rainfall over m days at gauge k

The procedure adopted by Porter and Ladson (1993) was used for this study, with the following modifications.

- If there are one or more rainfall stations having concurrent data within 5 km of the reference station (maximum of 3 stations), the proportions of daily rainfall at those stations are used with equal weights for disaggregation of accumulated rainfall totals at the reference station. If data are available from only one station, the proportions of daily rainfall at that station are used.

- If there are no stations within 5 km having concurrent data, data from the nearest three stations (within 50 km) are used for disaggregation, using the weighting procedure given by Eq. 3.2.

- If none of the nearest 15 stations has concurrent data over the accumulated period, disaggregation is generally considered to be infeasible. However, if the accumulated total is less than 5 mm, it is uniformly distributed over the accumulated period.

For satisfactory results, pre-screening of the data to exclude the stations having obvious errors, such as shifts in timing etc., may be required. Rainfall amounts disaggregated in this way are expected to be more uniform than the actual, so the number of stations involved in the weighting procedure was limited to three.

Disaggregation of accumulated totals may result in a reduction in the number of combinations of stations to be dealt with for estimation of areal rainfall. This in turn reduces computer time.

3.3 Fine-tuning of the methodology and sensitivity analyses

3.3.1 Purpose of investigations

The proposed methodology outlined in Section 3.1 was subject to a number of exploratory runs in its development, in particular, to fine-tune various modules of the methodology and to ascertain that the results would not be unduly affected by variable conditions of data availability. The purpose of carrying out those exploratory runs can be summarised as:

- To test alternative frequency distributions with respect to sampling variability and consistency of the results, in order to select the statistically most robust procedure for application.

- To examine sensitivity of the results to criteria adopted in determination of annual maximum areal and point rainfall series and in screening those series for frequency analysis.

- To examine whether variable input data conditions, such as use of different record lengths and station densities, could introduce undue bias or trends in the results.

- To provide an indication of spatial variability and trends in the derived areal reduction factors.

3.3.2 Description of investigations

This section gives a brief description of the exploratory runs made to investigate the issues outlined in the previous section. Reference should be made to Siriwardena and Weinmann (1996) for a comprehensive description of the investigations.

3.3.2.1 Evaluation of alternative frequency distributions

A Generalised Extreme Value (GEV) distribution and an empirical distribution based on the Cunnane plotting position formula were considered as alternative procedures for frequency analysis of annual maximum areal and point rainfall series in the derivation of ARFs. Test runs were carried out for a large number of circular 'catchments' of different sizes located in a region having a relatively dense network of stations (Rainfall Districts 85 and 86). The derived ARFs from the two procedures were compared and evaluated in relation to sampling variability (standard error as a measure) and consistency, over a range of AEPs and rainfall durations.

It was shown that the estimates of ARFs derived from the two alternative frequency distributions (a GEV distribution and empirical distribution based on Cunnane plotting position formula) are acceptably close, the differences being mostly within 2% for all catchment sizes and durations. The estimates based on the GEV procedure were found to be robust, consistent and less variable, probably because of the smoothing inherent in fitting a theoretical distribution. The GEV procedure also provides a more orderly and uniform variation of ARFs over the range of AEPs tested. Therefore, the procedure based on the GEV distribution was selected for derivation of ARFs in this study.

3.3.2.2 Effect of station network density on areal reduction factors

Areal reduction factors for Victoria are, of necessity, based on rainfall data from variable network densities for different regions that cover non-concurrent periods. As a result, the test 'catchments' used in the derivation of ARFs are subject to spatially and temporally variable data.

The aim of this test was to investigate the effect of station network density on the ARFs and the associated sampling variability, in particular, to examine whether there are any reproducible biases and trends in the ARFs derived using different networks. In examining the regional variation of ARFs it is necessary to ascertain that such trends or biases do not obscure the true nature of the regional variation.

Test runs were made for circular 'catchments' of different sizes selected from a denser network area (Rainfall District 86). For each catchment, a number of different combinations of rainfall stations, with 75%, 50% and 25% of the total number of stations were selected using a random number generator. A typical plot of ARF against the number of station-years is given in Figure 3.2 in which the number of station-years involved in the computation of ARF was considered as a measure of station network density.

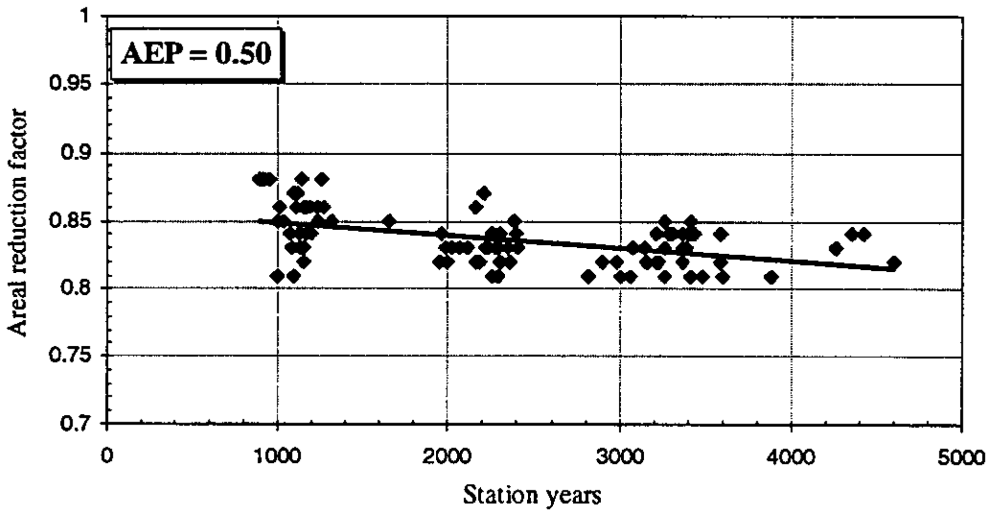


Figure 3.2 : Effect of station density on areal reduction factors

The test runs indicated that there is a slight tendency to overestimate ARFs, if they are derived from less dense networks. For 24 hours duration, this tendency was shown to be high as 3% across the extremes of station densities and found to be more pronounced for 24 hours duration than for longer durations. However, as there is a smaller variation of station network density across the state compared to the range of densities tested, this is not expected to unduly affect the magnitude and spatial variation of the ARFs. It was also observed that there is a higher sampling variability of the ARF associated with a lower density of the station network.

3.3.2.3 Effect of initial period of data record

The station network density in 1993 is approximately equal to that in 1900, but there was only a sparse network of stations prior to 1890 (Siriwardena and Weinmann, 1996). If the base period for this study was restricted to only the later period, such as 1900-1993, more uniform data conditions over the simulation period could be achieved. On the other hand, long records would be important for frequency analysis, especially in deriving estimates for low probabilities. The aim of this test was to investigate the effect of exclusion of the data from the early period, especially to examine whether the ARFs so derived would be significantly different.

The test involved comparing ARFs derived for 75 test 'catchments' of the same size, selected from Rainfall District 86, using daily rainfall data from 1900 to 1993 and from the start of the record to 1993.

The results indicated that only small differences in the magnitudes of the ARFs were observed when the base period was restricted to the later period of 1900-1993. It is therefore recommended that the whole period of record be used for the derivation of ARFs.

3.3.2.4 Criterion for minimum number of stations for estimation of areal rainfall

The accuracy of the areal rainfall estimates depends on the ability to account for areal variability of rainfall during storm events. This can be achieved by having a sufficient number of stations uniformly distributed over the catchment. In general, it would be difficult to maintain this accuracy over the entire period of study, due to different number of stations being operated at different times, especially during early periods (before 1900).

A criterion, defined as a function of catchment area, was used to determine the minimum acceptable number of stations required in estimating areal rainfall. In determining such a criterion a balance was needed between accuracy and data utilisation, as a more stringent criterion would adversely reduce the length of the annual maximum series.

A sensitivity analysis was carried out for circular 'catchments' ranging from 500 to 2000 km^2 (in Rainfall District 86) with estimation of areal rainfall subject to a number of different criteria for determining minimum number of stations required.

The investigations showed that the criterion set out in Section 3.1.2 is acceptable. The sensitivity analysis showed only small differences in the sample mean ARF values (generally less than 1%) derived using different criteria. It is therefore concluded that the results are not sensitive to small variations in the above criteria.

3.3.2.5 Effect of minimum record length for fitting frequency distribution

The quantile estimates of point and areal rainfall are more accurate when a longer annual maximum series is used. In this study, only stations having annual maxima for at least 30 years are used in the regional procedure of fitting a GEV distribution in determining quantile estimates for representative point rainfall. Sensitivity of the ARFs to this criterion was tested by comparing the ARFs derived using 20 years as a minimum record length.

The investigations showed that the minimum number of 30 data values in the point and areal rainfall series used for the frequency analysis is acceptable. However, the sensitivity analysis showed only small differences in the sample mean ARF values (generally less than 1%) derived using the two criteria.

3.3.2.6 Preliminary results for two regions of dissimilar characteristics

As a preliminary investigation, ARFs were derived for two regions considered to be dissimilar in meteorological characteristics, ie. a wet coastal region (Rainfall District 85) and a dry inland region (Rainfall District 77). The aims of this preliminary investigation were:

- to assess the variability associated with the curve fitting procedure;
- to compare the results of the two districts for regional variability;
- to examine the variation of the ARFs with annual exceedance probability (AEP);

For each region, ARFs were derived for about 100 circular 'catchments', ranging up to an area of 6000 km^2. A power function was then fitted to each combination of rainfall duration and AEP to express the relationship between ARF and area.

The preliminary investigation of the ARFs for two rainfall districts of dissimilar characteristics indicated evidence for regional variability in the ARFs, especially for 24 hours duration. Hence, it was decided to conduct a comprehensive study for the regional variability of ARFs in Victoria.

3.3.3 Conclusions from investigations

Although the adopted procedure contained some minor inconsistencies in the treatment of the point and areal rainfall series (see Siriwardena and Weinmann, 1996), it was found to perform satisfactorily in the preliminary investigations. Following this pilot study, the procedure was applied to the full data set (Chapter 4).

4. DERIVATION OF DESIGN VALUES OF AREAL REDUCTION FACTORS FOR VICTORIA

This chapter is devoted to a detailed account of the determination of design values of areal reduction factors (ARFs) for Victoria using the modified Bell's method described in Chapter 3. The study initially investigated the significance of the regional variability of the computed ARFs, and then evaluated the appropriateness of deriving ARFs on a regional basis in relation to hydrometeorological factors. The design values were based on individual ARF values computed for a large number of circular 'sample catchments' distributed over a single region encompassing the whole State of Victoria. These sample ARF values were determined for rainfall durations of 1, 2 and 3 days, and for a range of catchment areas and AEPs. The sample mean values for each combination were then used to fit a single equation, to represent the dependence of ARF values on rainfall duration, catchment area and AEP. The development of this relationship is discussed in detail in the latter part of this chapter.

4.1 Investigation of regional variability in areal reduction factors

Any pooling of data to determine regional average values of a hydrological characteristic requires an assumption that the region is homogeneous with regard to the physical factors reflected in that characteristic. With regard to ARFs for Victoria, it is quite likely that any regional differences in the dominant storm mechanisms producing the annual rainfall maxima would translate into regional differences in the derived ARFs. For example, a region predominantly subject to frontal storms could have significantly different ARFs to those for a region in which annual maxima generally result from thunderstorms.

It was therefore necessary to investigate the regional variability of the ARFs derived for Victoria. This was carried out by dividing the State initially into several regions on the basis of topographical and meteorological considerations and then testing statistically, whether the regional mean values of ARFs were significantly different. Following analysis of these results, modified regions were formed by combining the congruent regions and then testing them for regional differences of ARFs. A detailed description of these investigations is given in Siriwardena and Weinmann (1996).

4.1.1 Tests for significance of regional differences in derived areal reduction factors

Figure 4.1 shows the modified regions identified from the initial analysis. The south-western part of the state, excluding the Otway Ranges, forms the RH Region with the highest values of ARFs. The southernmost part of the state, the RL Region with the lowest ARF values, could be described as mountainous coastal areas with high mean annual rainfall. The rest of the state forms the largest region, the RM Region, which includes the northern dry region, the south eastern coastal region, as well as the central divide of high rainfall. However, large areas of the north-eastern and south-western part of this region are devoid of representative 'catchment' data points, due to the very sparse network of rainfall stations. This made it difficult to explain the variation of ARF with respect to physical factors and to clearly delineate the boundaries of regions in these areas.

Statistical significance tests (t-tests) were used to assess differences in the regional sample mean values of ARFs (for given combinations of catchment size, rainfall duration and AEP). These tests indicated that the mean value of ARFs for Region RL is significantly different (at the 5% level) from that for Regions RM and RH for nearly all probabilities and durations. For higher AEPs (eg. 0.50, 0.10), the mean ARFs for the Region RM are not significantly different from the mean values for Region RH at the 5% level, but are significantly different for lower AEPs.

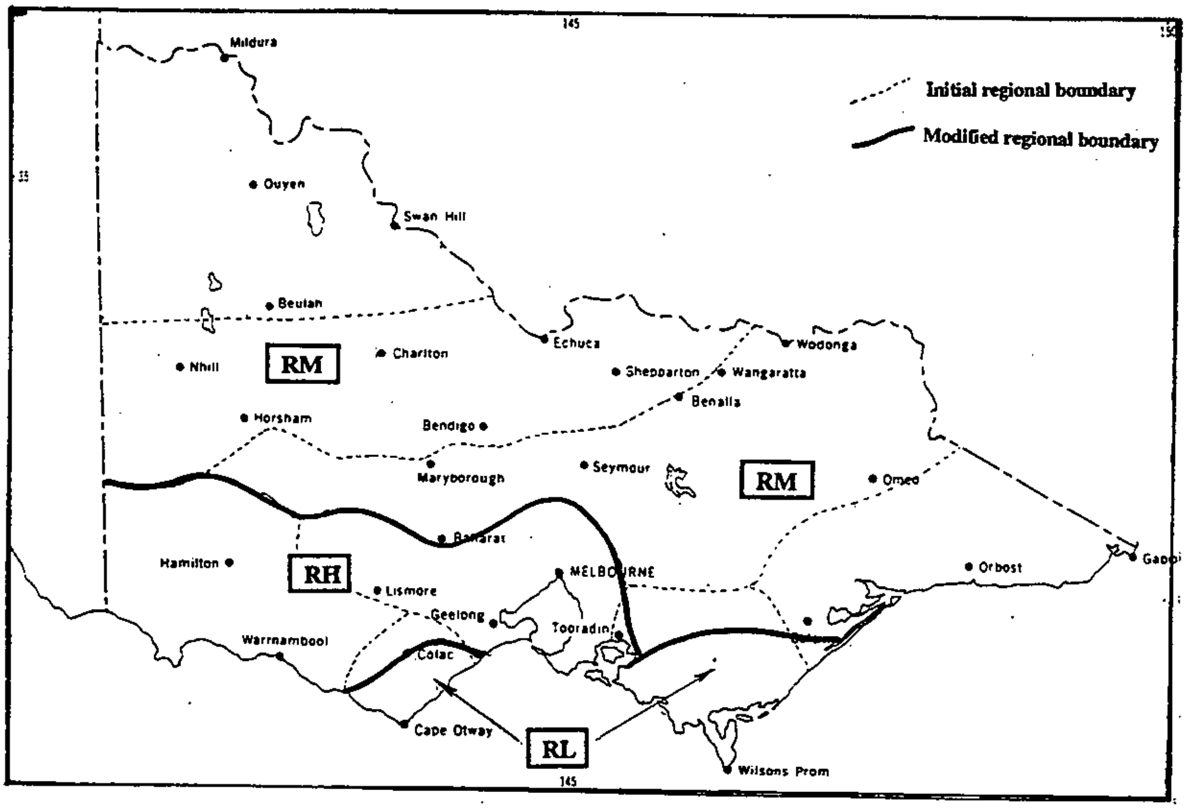


Figure 4.1 : Boundaries of modified regions for investigating regional variability of ARFs

The statistical tests for regional variability of areal reduction factors in Victoria support the following conclusions:

- The State of Victoria can be subjectively divided into three separate regions with significant differences in the ARF values, at least for large catchment areas (1000 km^2) and low AEPs (0.02 and 0.01).
- For this range of areas and AEPs the differences between the regions with highest and lowest ARF values are in the order of magnitude of 5 to 10 %.
- The ARFs for the coastal regions of Otway Coast and South Gippsland are smaller than the ARFs for the rest of the State.
- The regional differences in ARF values for smaller catchment areas (250 km^2) and for more frequent rainfalls (AEP of 0.5 and 0.1%) are not so pronounced, but consistent with the trends observed for larger areas and lower AEPs.
- The magnitude of the regional differences in ARF values is generally less than the difference between the values from this study and the corresponding values recommended in ARR87. Only the ARF values for the mountainous coastal regions indicate a departure from the values for the other regions (5-10% difference between highest and lowest).

4.1.2 Assessment of regional variability based upon meteorological factors

The delineation of regions for ARF values on the basis of the analysis described above is made difficult by the fact that the true differences in rainfall characteristics are masked by the effects of sampling variability. It is thus very important to understand the significance of the demarcation of the regions with respect to either meteorological or physical catchment characteristics, and the underlying phenomena that cause the differences in the ARFs. The boundaries of the modified regions thus need to be subject to the confirmation through hydrometeorological assessment. This assessment is only qualitative, based on discussions with hydrometeorologists from the Bureau of Meteorology.

This study concentrates on deriving *fixed-area* ARFs on a probabilistic concept. The ARFs are computed from the separate frequency analysis of annual maximum areal rainfalls and point rainfalls. Both the annual maximum areal rainfall and point rainfall series are a mixture, resulting from different types of storms such as thunderstorms and frontal storms. This makes it difficult to relate the magnitude of ARFs directly to the meteorological parameters. This fact may be contrasted with the relative convenience of relating meteorological factors to the *storm-centred* ARFs, which involves analysing storm profiles of individual storms.

However, the dominance of one storm mechanism in a particular region can be expected to reflect in the magnitude of ARFs. For example, in an area for which thunderstorms are dominant over frontal storms, the annual maximum point rainfall series may primarily be constituted of intense rainfalls from thunderstorms. On the other hand, due to the fact that frontal storms are more widespread, the annual maximum areal rainfall series may primarily correspond to rainfalls from frontal storms. This would result in relatively low areal reduction factors for a region dominated by thunderstorms compared to those for a region subject to more frequent frontal storms. This effect is more pronounced for ARFs derived for short durations. Unfortunately, there is at present no readily available information on the prevalence of different storm mechanisms in different parts of Victoria.

Although the regional differences in the areal reduction factor cannot be fully explained through meteorological characteristics, the observed differences between the three demarcated regions could be qualitatively related to the dominance of storm mechanisms. The low ARFs associated with the mountainous coastal region could be attributed to the possible dominance of thunderstorms which are likely to be caused by the prevailing south-eastern low pressure systems. Although it is expected that this coastal region of low ARFs would extend to the south-east coast, the results of this study do not show clear evidence to support this. Similarly, dominance of frontal storms over thunderstorms could be the reason for relatively high ARFs in the south-western region. It was also noted that considerable small-scale variations exist in the magnitude of ARFs, especially in the north-west of the state.

While hypothesis tests indicated evidence of regional variability in ARFs, the underlying meteorological factors associated with the regional variability of ARFs are not clearly understood at this stage. This makes an exact delineation of regional boundaries difficult, if not impossible. It may also be noted that, at present, results of similar studies are not available for regions outside Victoria; but it would be beneficial to analyse the regional variability over a larger area (beyond the state boundaries) with more emphasis on the regional integrity.

In the absence of studies which provide clear evidence on the nature of regional variability of ARFs and of a rational basis for delineating regions, it was decided to consider the whole of Victoria as a single region.

4.2 Derivation of areal reduction factors using modified Bell's method

Determination of design values of ARFs for Victoria was based on individual ARF values computed for a large number of circular 'sample catchments' of a range of sizes distributed over those parts of Victoria with a relatively high rain gauge density. For each catchment, ARFs were derived for rainfall durations of 1, 2 and 3 days and for a range of AEPs. The sample mean ARF values calculated for different combinations of catchment sizes, durations and AEPs were then used to define a relationship for ARF as a function of catchment area, rainfall duration and AEP (considering the whole of Victoria as a single region). This relationship was adopted for determining design values of ARF.

4.2.1 Selection of catchments for derivation of areal reduction factors

In this study, circular 'catchments' of different sizes located to give an even distribution over the State was the basis for deriving ARF values. The selected sizes of catchments were 125, 250, 500, 1000, 2000, 4000 and 8000 km^2 (to give an equal spacing on a logarithmic scale). The basic criterion for locating these sample 'catchments' was the station network density. As a result, certain regions such as the north-west, central ranges, north-east and East Gippsland were devoid of sample catchments, because there were insufficient stations for the analysis (Figure 3.1). The circular catchments were also located to partly overlap, in order to obtain an adequate number of samples, while assuring that different combinations of stations are involved in the analysis. As it would have been difficult in smaller catchments to satisfy the criterion of minimum station network density at more than just a few locations, the smallest catchment size for the analysis was set at 125 km^2. The number of sample 'catchments' ranged from 180 to 30 for areas of 1000 and 8000 km^2 respectively. As an example, the layout of circular catchments for 1000 km^2 over the whole State is shown in Figure 4.2.

4.2.2 Derivation of sample mean values

Areal reduction factors were derived for each circular catchment for three durations (1, 2 and 3 days) and for six AEPs (0.5, 0.2, 0.1, 0.05, 0.02 and 0.01). The derivation was based on the modified Bell's method described in Chapter 3, subject to satisfying the criteria for adequacy of rainfall station network and length of data records. The catchments which did not satisfy the criterion of minimum number of stations involved in the computation of areal rainfall were discarded. Similarly, estimates for AEPs lower than 1 in 50 were not computed from short records. The ARF values derived for a range of catchments analysed in this study are presented in Siriwardena and Weinmann, 1996 (Appendix B).

Sample mean values of ARFs, derived for Victoria as a single region, for various combinations of areas, durations and AEPs, together with the number of samples involved in computation are given in Table 4.1. The ARFs ranged from 0.74 (for an area of 8000 km^2 and AEP of 0.01) to 0.96 (125 km^2 and AEP of 0.50). These sample mean values will be used to derive design relationships for ARF values in Victoria (Section 4.3).

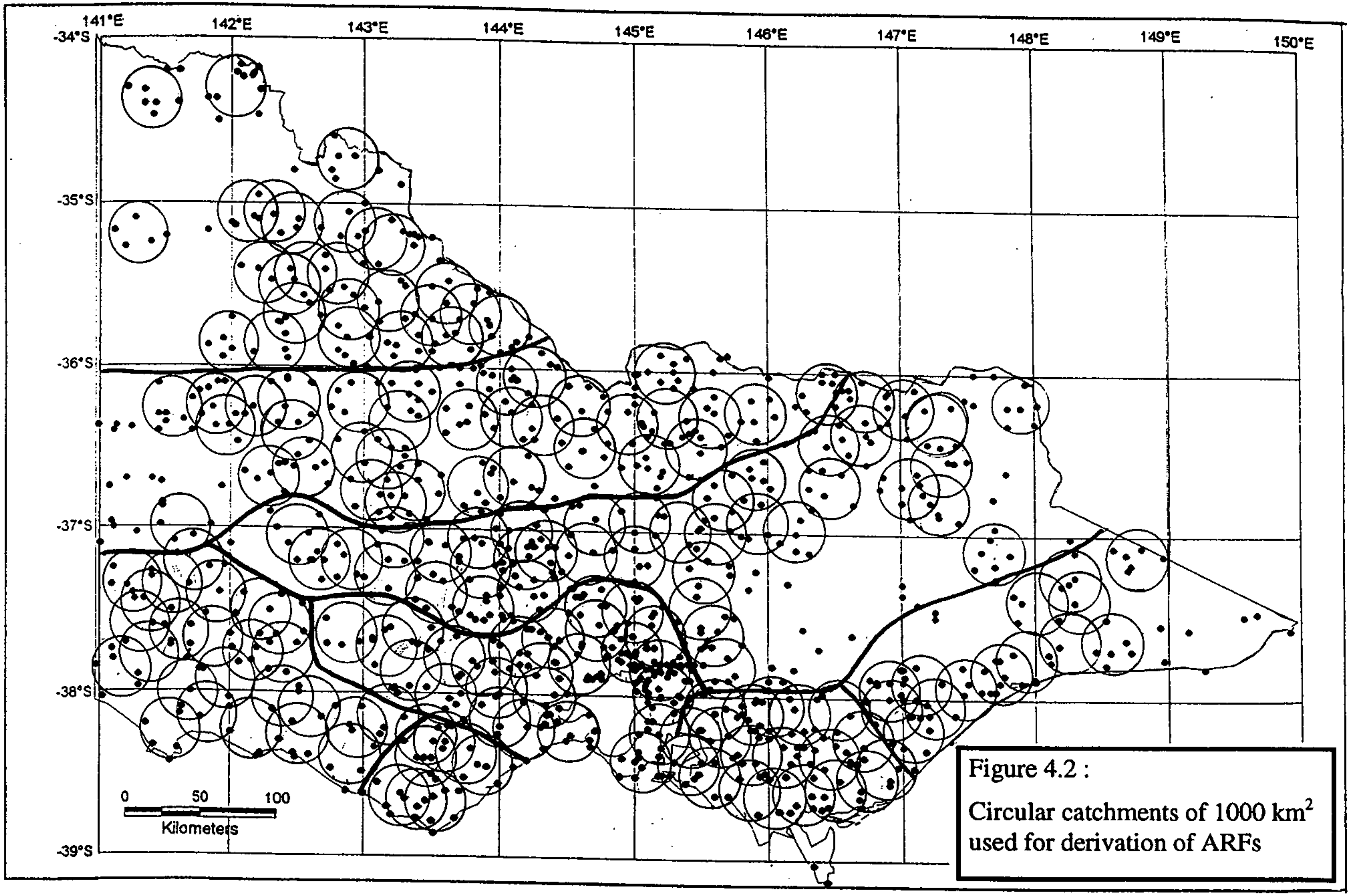


Figure 4.2 :

Circular catchments of 1000 km^2 used for derivation of ARFs

Table 4.1: Sample mean values of areal reduction factors (ARFs) for Victoria (24 to 72-hour durations)

(a) Sample mean ARFs for *24-hour duration*

Area (km^2)	Number of rep. areas	Annual Exceedance Probability (AEP)					
		0.5	0.2	0.1	0.05	0.02	0.01
125	119	0.91	0.90	0.90	0.90	0.90	0.89
250	178	0.90	0.90	0.90	0.89	0.89	0.89
500	157	0.87	0.87	0.87	0.87	0.87	0.88
1000	180	0.86	0.85	0.85	0.85	0.85	0.85
2000	96	0.83	0.82	0.82	0.81	0.81	0.80
4000	52	0.81	0.79	0.79	0.78	0.77	0.77
8000	30	0.78	0.77	0.76	0.75	0.74	0.74

(b) Sample mean ARFs for *48-hour duration*

Area (km^2)	Number of rep. areas	Annual Exceedance Probability (AEP)					
		0.5	0.2	0.1	0.05	0.02	0.01
125	119	0.95	0.94	0.94	0.94	0.94	0.93
250	178	0.94	0.94	0.93	0.93	0.93	0.93
500	157	0.92	0.92	0.92	0.92	0.92	0.92
1000	180	0.91	0.91	0.90	0.90	0.90	0.89
2000	96	0.89	0.88	0.87	0.87	0.86	0.86
4000	52	0.88	0.86	0.85	0.84	0.84	0.83
8000	30	0.85	0.84	0.83	0.82	0.81	0.80

(c) Sample mean ARFs for *72-hour duration*

Area (km^2)	Number of rep. areas	Annual Exceedance Probability (AEP)					
		0.5	0.2	0.1	0.05	0.02	0.01
125	119	0.96	0.96	0.95	0.95	0.95	0.95
250	178	0.96	0.95	0.95	0.95	0.95	0.95
500	157	0.94	0.94	0.94	0.93	0.93	0.93
1000	180	0.93	0.92	0.92	0.92	0.91	0.91
2000	96	0.92	0.90	0.90	0.89	0.88	0.88
4000	52	0.90	0.89	0.88	0.87	0.86	0.85
8000	30	0.88	0.86	0.85	0.84	0.83	0.82

4.2.3 Measures of variability associated with derived areal reduction factors

It was stated in Chapter 3 that variable data conditions may contribute to an increased sampling variability of the derived areal reduction factors. The standard deviation and 95% prediction interval are two useful indicators of the sampling variability associated with the derived ARF values. Similarly 95% confidence interval of sample mean would give an indication of the accuracy of the estimated sample mean ARF values.

The standard deviations of the derived ARF values for different combinations of areas, durations and AEPs are given in Table 4.2. This table clearly indicates that the standard deviation decreases with increasing AEP, catchment area and rainfall duration. Sample mean ARF values, 95% prediction limits of derived ARFs and 95% confidence limits of sample means for a range of areas, durations and AEPs are presented in Figure 4.3. This information allows an assessment of the probable accuracy of the derived ARFs and the estimated mean values.

As shown in Table 4.2 and Figure 4.3, the sampling variability of the *derived ARFs* decreases as the area increases. Uncertainties associated with the derived ARFs for small catchments are quite large, as the areal and point rainfall estimates are based only on a small number of stations with non-concurrent data. It should also be remembered that sample catchments are not independent and have been selected to partly overlap, in order to have an adequate number of samples. This may have an effect on the sampling variability as the samples for small catchment sizes are generally independent, whereas those for large catchments partly overlap. Similarly, the sampling variability of the ARFs tends to increase for lower AEPs, which is attributed to the higher uncertainty in the estimates of areal and point rainfall for lower probabilities, especially when using data of variable record length. In this respect, ARF estimates for AEP of 0.50 are considered to be the most accurate. The tendency for reduced sampling variability with increased rainfall duration may be attributed to the more complete storms being included in the analysis of longer duration rainfalls.

The confidence interval for the *sample mean of ARF values* is a function of the variance of the derived ARF values and the number of sample catchments used; the larger the number of sample catchments used, the more accurate is the estimated mean. Although the variance is smaller for the larger catchments, the estimate is based on fewer sample catchments; hence only tentative conclusions can be drawn for the accuracy of the estimated mean in relation to catchment area. It appears that the sample mean values of ARF for catchment areas in the range from 250 to 2000 km^2 are most accurate. However, the accuracy of the sample mean is shown to be lower (ie. a wider confidence interval) for lower AEPs. Figure 4.3 indicates that the trend of mean ARF values with catchment area is quite well defined.

Table 4.2: Standard deviation of derived areal reduction factors (ARFs)

(a) Standard deviation of ARFs for *24-hour duration*

Area (km^2)	Number of rep. areas	Annual Exceedance Probability (AEP)					
		0.5	0.2	0.1	0.05	0.02	0.01
125	119	0.042	0.043	0.046	0.053	0.070	0.085
250	178	0.041	0.042	0.044	0.049	0.060	0.067
500	157	0.039	0.037	0.039	0.044	0.056	0.060
1000	180	0.038	0.039	0.043	0.049	0.063	0.064
2000	96	0.029	0.028	0.029	0.034	0.044	0.055
4000	52	0.028	0.029	0.029	0.033	0.041	0.047
8000	30	0.023	0.025	0.026	0.032	0.043	0.054

(b) Standard deviation of ARFs for *48-hour duration*

Area (km^2)	Number of rep. areas	Annual Exceedance Probability (AEP)					
		0.5	0.2	0.1	0.05	0.02	0.01
125	119	0.033	0.035	0.038	0.045	0.060	0.068
250	178	0.032	0.033	0.035	0.041	0.053	0.058
500	157	0.029	0.031	0.034	0.040	0.052	0.060
1000	180	0.029	0.033	0.037	0.045	0.057	0.057
2000	96	0.023	0.024	0.027	0.031	0.041	0.051
4000	52	0.025	0.026	0.027	0.029	0.038	0.046
8000	30	0.020	0.024	0.027	0.032	0.040	0.047

(c) Standard deviation of ARFs for *72-hour duration*

Area (km^2)	Number of rep. areas	Annual Exceedance Probability (AEP)					
		0.5	0.2	0.1	0.05	0.02	0.01
125	119	0.030	0.031	0.035	0.043	0.056	0.063
250	178	0.031	0.032	0.035	0.040	0.052	0.055
500	157	0.030	0.032	0.035	0.042	0.054	0.061
1000	180	0.029	0.033	0.037	0.043	0.054	0.050
2000	96	0.024	0.025	0.027	0.030	0.037	0.045
4000	52	0.021	0.022	0.023	0.028	0.039	0.044
8000	30	0.023	0.025	0.026	0.028	0.033	0.039

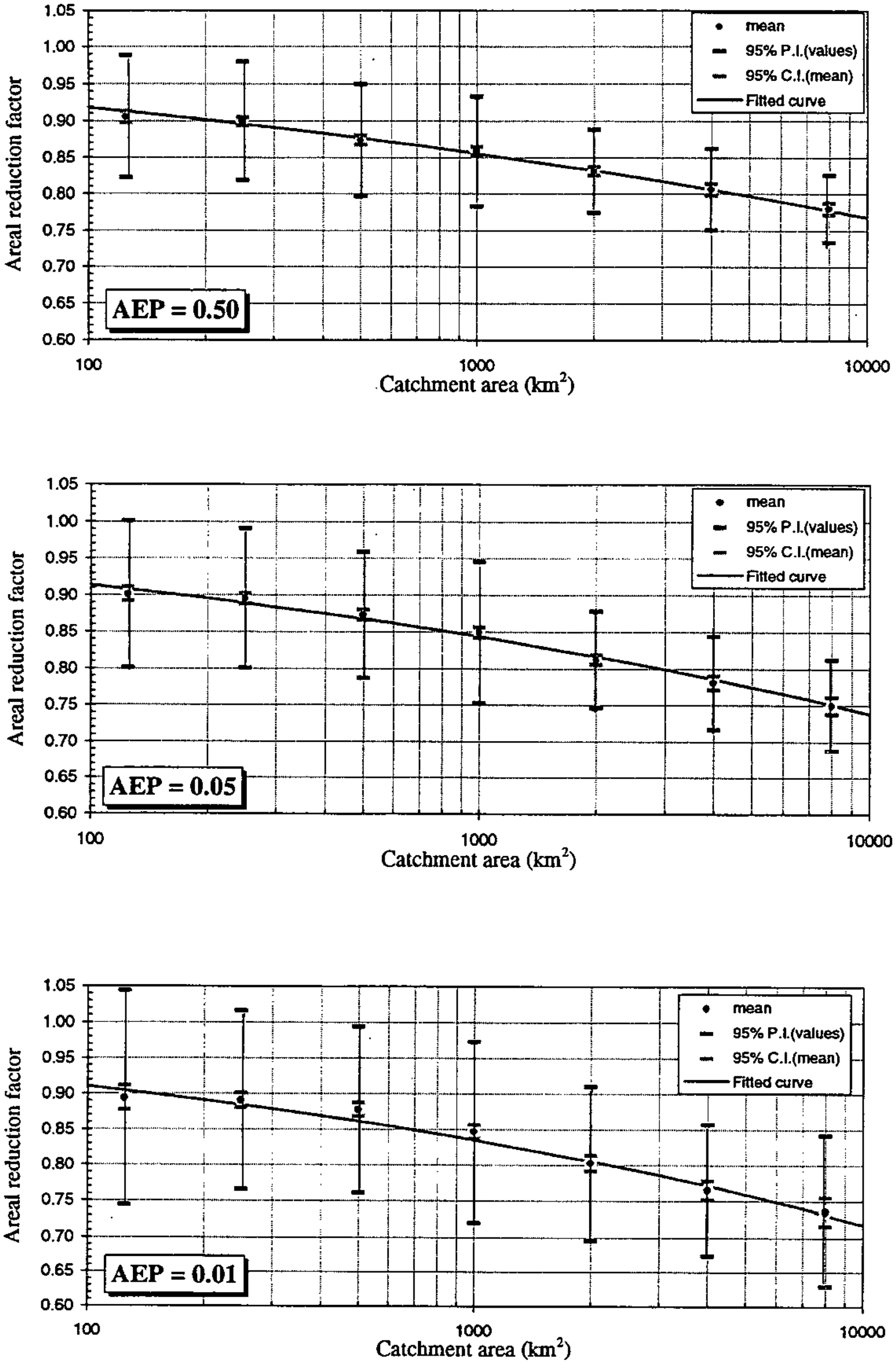


Figure 4.3: Prediction limits of areal reduction factors and confidence limits of sample mean
(a) 24 hour duration

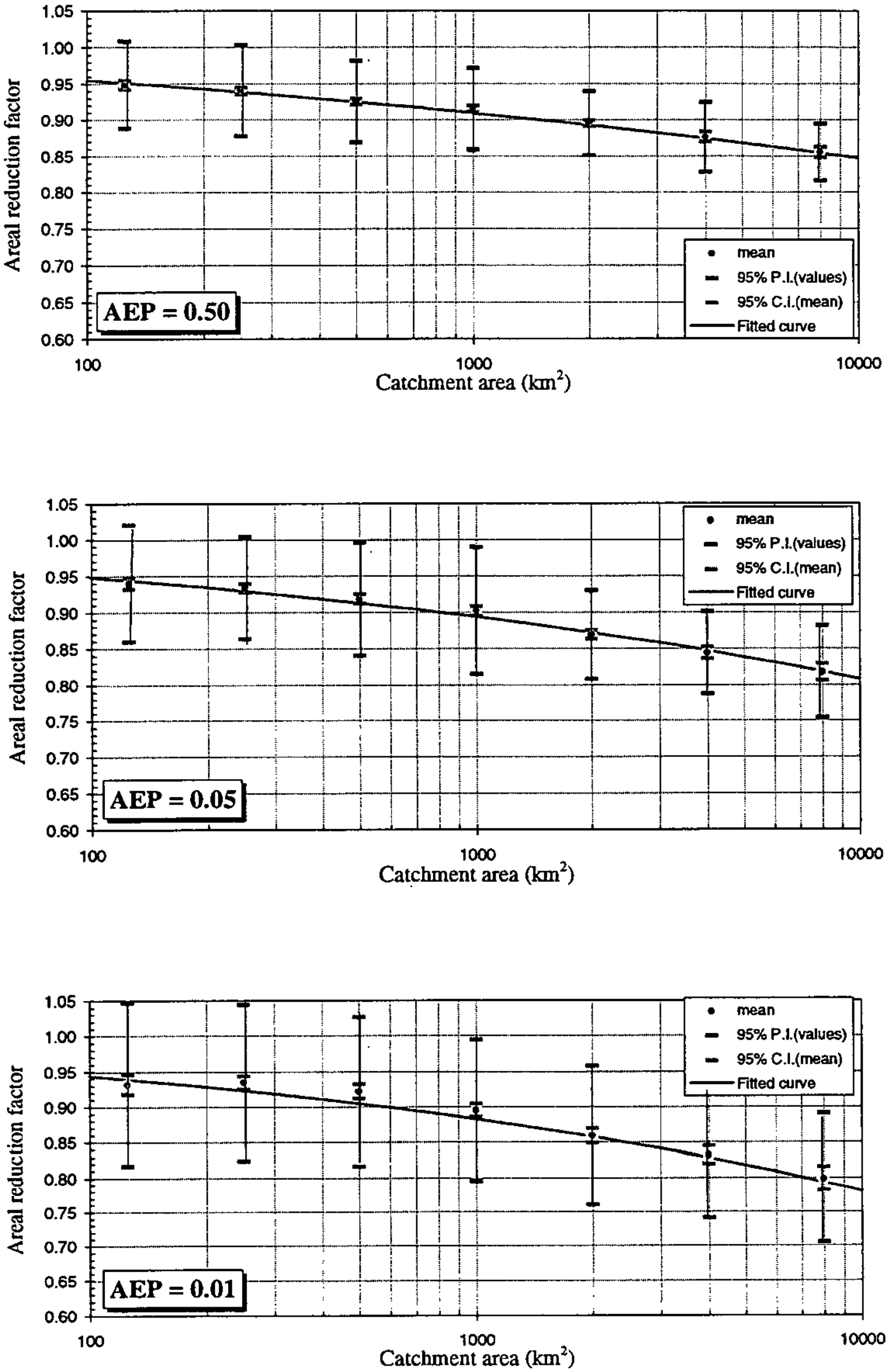


Figure 4.3 : Prediction limits of areal reduction factors and confidence limits of sample mean
(b) 48 hour duration

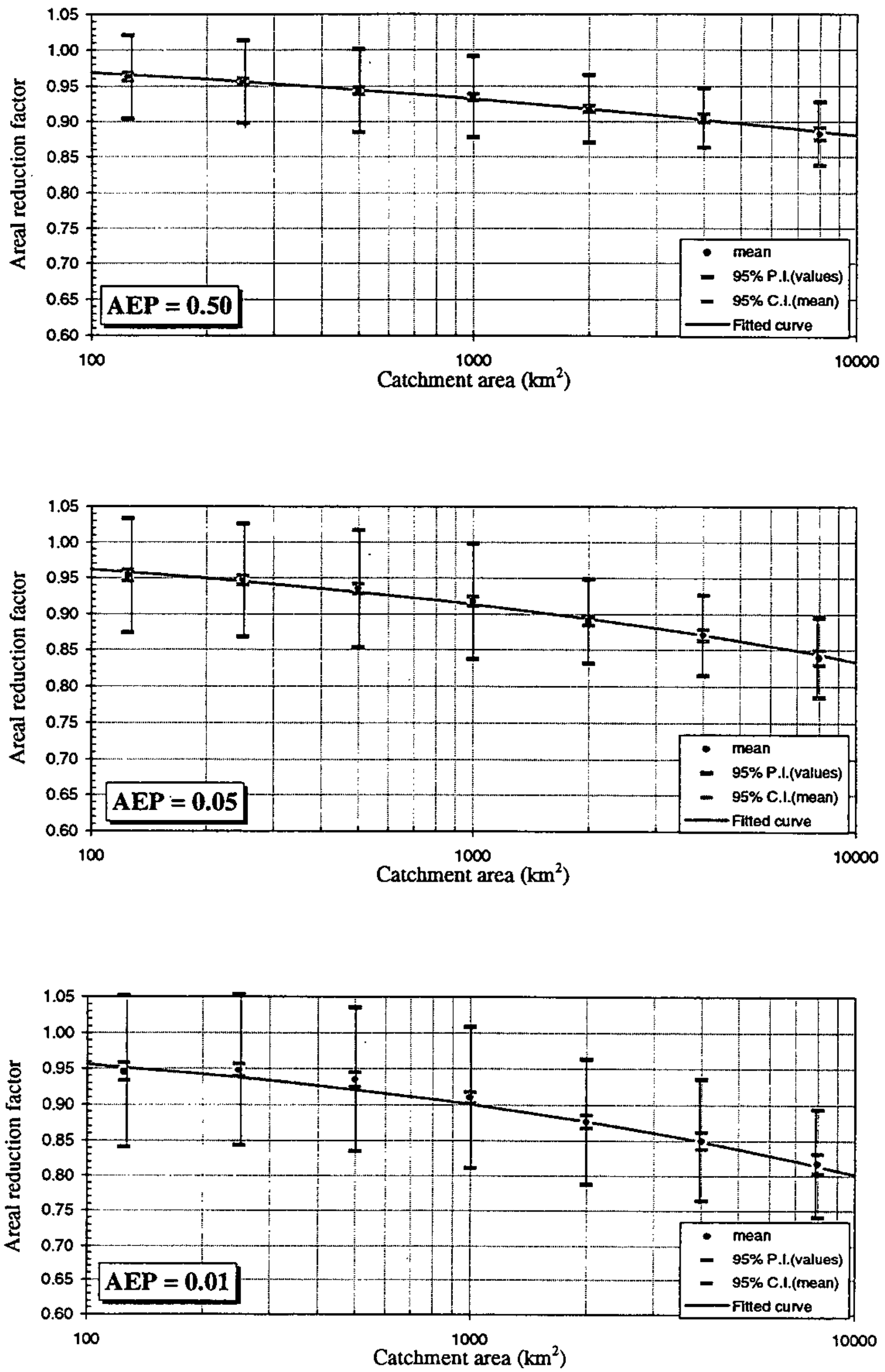


Figure 4.3 : Prediction limits of areal reduction factors and confidence limits of sample mean
(c) 72 hour duration

4.3 Fitted curves for areal reduction factors

The design values of areal reduction factors will be based on the functional relationships established between the sample mean values of ARFs and the variables of catchment size, rainfall duration and AEP. Such curves or mathematical relationships can then be used to estimate ARFs for other catchment sizes, durations and AEPs than those sampled. The limits of the applicability of the relationship for extrapolation also need to be defined. As the functional relationships will be based on the ARFs derived for only three durations (24, 48 and 72 hours), particular care will be needed in extrapolating the results to other durations, specifically durations less than 24 hours. At this stage it will not be possible to assess the compatibility of the results of this study with ARFs for durations less than 24 hours from Victorian data, as these will only be derived in a future CRC project.

4.3.1 Initial forms of relationship for areal reduction factor

A number of alternative forms of relationships given in the literature and their modifications were initially considered for fitting a single relationship for ARF that explains the variation with catchment area, rainfall duration and annual exceedance probability.

The relationships were generally of non-linear form, and were fitted to sample mean ARFs for a range of areas, AEPs and durations (126 data points). The assessment of the accuracy of the fit of the curves was based on how well the fitted curves matched the plotted sample mean values, as indicated by statistical measures such as the coefficient of determination (R^2) and the standard error (SEE). The different relationships considered, their performance and deficiencies are discussed in detail in Siriwardena and Weinmann (1996).

The deficiencies in the initial relationships for ARF can be summarised as :

- Lack of inter-relationship between duration and AEP; eg. less dependency of ARF on AEP as the duration increases, which is contradictory to the tendency exhibited by the sample data.
- The limiting values of A_0 (area at which the ARF approaches 1.0) as optimised by the fitting procedure appear to be either too high or too low.
- Extrapolation to other durations appears to be unsatisfactory.
- Inadequacy of the fit, in particular, to the sample data for 24-hour duration.

4.3.2 Adopted relationship for areal reduction factor

Experience with fitting the initial relationships indicated that the following factors need to be considered when establishing an improved relationship for areal reduction factors:

- As shown in Section 4.2.2, the derived ARFs are most accurate for an AEP of 0.5; hence, more emphasis needs to be given to fit these estimates accurately.

- In addition to the statistical performance criteria such as R^2 and SEE, the adequacy of a fitted relationship should be justified visually by comparing plots of the fitted curves and sample data points.
- In the absence of data points in this range, extrapolation of the established relationship to catchment areas less than 100 km^2 is somewhat subjective. It would therefore be desirable for the fitted curves to approach the limiting value of ARF of 1.0 at an area considered to be of practical significance (eg. 1 to 5 km^2 for the range of durations from 24 to 72 hours).
- Extrapolation of the relationship to other durations (over a limited range) needs to produce satisfactory results.
- The established relationship between the ARF and AEP needs to be supported by available evidence at probabilities lower than those derived (ie. AEP < 0.01).

Based upon the above considerations, the relationship for ARF was derived in two stages. A relationship for *ARF for an AEP of 0.50* was first established as a function of area (AREA) and rainfall duration (DUR). Based on this relationship, a function representing the correction for other AEPs was then derived.

ARF for AEP = 0.50

After considering a number of alternatives, the following form of relationship was adopted.

$$ARF_{0.50} = 1.00 - a(AREA^{b} - c\log_{10} DUR)\cdot DUR^{d} \qquad (4.1)$$

where a, b, c, d = coefficients determined by regression

The underlying assumption in the above relationship is that the ARF approaches 1.0 as the area reduces to a minimum value proportional to the logarithm of rainfall duration. This is consistent with the notion that longer duration storms tend to be uniform over large areas.

The non-linear relationship shown in Eq. 4.1 was fitted to *sample mean ARFs of AEP of 0.50* derived for 7 different catchment areas, and 3 durations (21 data points) to determine the four regression coefficients. The resultant relationship is given in Eq. 4.2.

$$ARF_{0.50} = 1.00 - 0.4(AREA^{0.14} - 0.7\log_{10} DUR)\cdot DUR^{-0.48} \qquad (4.2)$$

No. of data points (N)	= 21
Coefficient of determination (R^2)	= 0.998
Standard error	= 0.003
	= 0.28% (as a % of the mean ARF)

Range of application : $1\ km^2 \le Area \le 10{,}000\ km^2$

$18\ hours \le Duration \le 120\ hours$

The fitted curves for 24, 48 and 72 hour durations together with sample mean values are shown in Figure 4.4. This figure also shows curves extrapolated over the full range of catchment areas and for the range of durations from 18 to 120 hours.

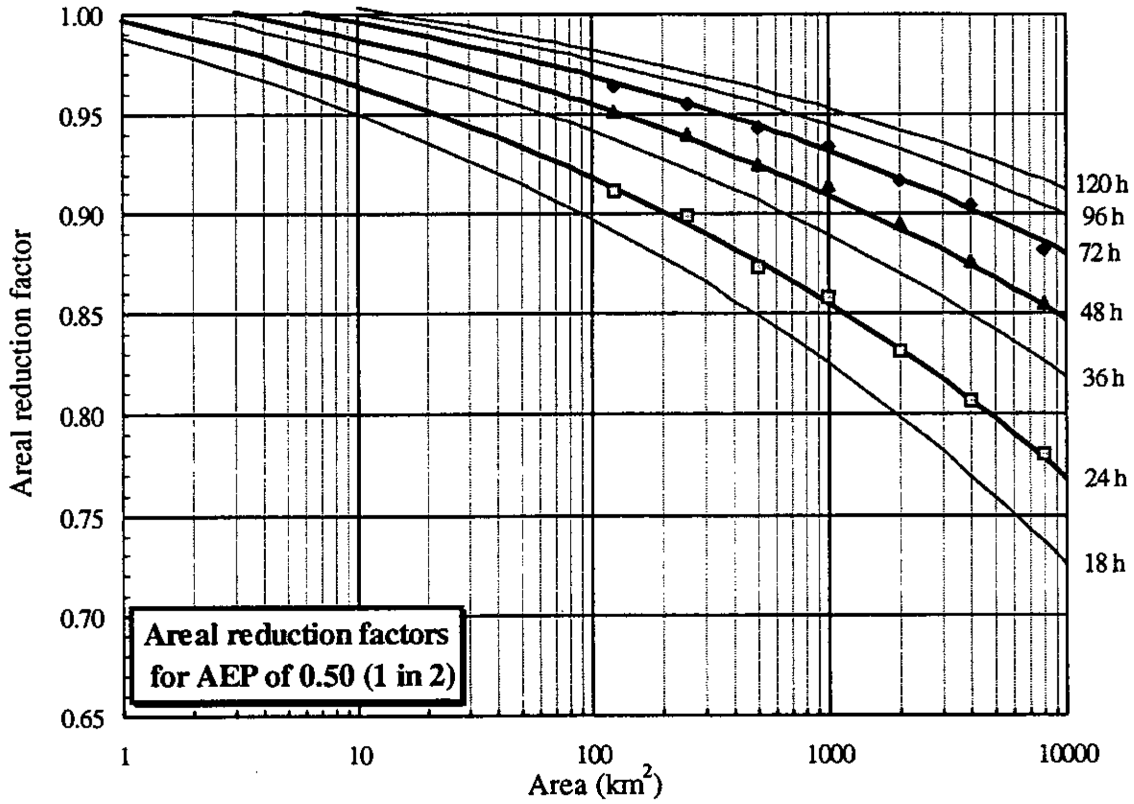


Figure 4.4 : Adopted areal reduction factor curves for AEP of 0.50 (1 in 2)

It can be concluded from Figure 4.4 that Eq. 4.2 provides a satisfactory fit to the *sample mean ARF values*. The extrapolation of the curves for the range of areas from 100 km^2 to 1 km^2, is virtually determined by the trend of the curve for the fitted range of catchment areas. The terminal catchment areas (areas at which the ARF approaches 1.0) worked out to be 0.8, 3 and 6 km^2 for durations 24, 48 and 72 hours respectively. These values are considered to be plausible, suggesting that the derived relationship can be used confidently to estimate ARFs for areas smaller than those sampled, with a lower limit of 1 km^2. The validity of the relationship for small areas was also confirmed by comparing the fitted curves with those given in the Flood Studies Report (NERC, 1975) and those derived by Stewart (1989) (see Figure 5.1 in Chapter 5).

Extrapolation of the relationship for other rainfall durations needs to be limited to a small range outside the range of calibration, since only ARFs derived for three durations have been used in establishing the relationship. The curves, extrapolated over the recommended range of durations (18 to 120 hours), were shown to be consistent with the results from other studies (NERC, 1975; Stewart, 1989), and are hence considered valid for this range.

ARF for AEP < 0.50

ARF values for AEPs of less than 0.50 are determined from the following relationship :

$$\mathrm{ARF}_{\mathrm{AEP}} = \mathrm{ARF}_{0.50} - \mathrm{kfac} \qquad (4.3)$$

where $\mathrm{ARF}_{\mathrm{AEP}}$ = ARF for AEP of interest (less than 0.50)

$\mathrm{ARF}_{0.50}$ = ARF for AEP of 0.50

The correction (kfac) applied to the reference relationship (Eq. 4.2) to estimate *ARF values for lower AEPs (< 0.50)* was found to be best represented by a function of the following form:

$$\mathrm{kfac} = \mathrm{e.AREA}^{\mathrm{f}}.\mathrm{DUR}^{\mathrm{g}}.(\log_{10}(0.5) - \log_{10}(\mathrm{AEP})) \qquad (4.4)$$

The underlying assumption in the above equation is that the relationship between ARF and the logarithms of AEP is linear. The justification for this assumption is discussed in detail in Section 4.4.

Substituting the fitted relationship for $\mathrm{ARF}_{0.50}$ and the assigned function for kfac in Eq. 4.3, ARFs for all AEPs can be computed from :

$$\mathrm{ARF}_{\mathrm{AEP}} = 1.00 - 0.4\,(\mathrm{AREA}^{0.14} - 0.7\log_{10}\mathrm{DUR}).\mathrm{DUR}^{-0.48} - \mathrm{e}\,(\mathrm{AREA})^{\mathrm{f}}.\mathrm{DUR}^{\mathrm{g}}.(0.3 + \log_{10}(\mathrm{AEP})) \qquad \text{..........}\,(4.5)$$

where e, f, g = coefficients determined by regression

The relationship given in Eq. 4.5 was fitted to *sample mean ARF values* (126 data points) to determine the three regression coefficients. The resultant relationship is given in Eq. 4.6.

$$\mathrm{ARF}_{\mathrm{AEP}} = 1.00 - 0.4\,(\mathrm{AREA}^{0.14} - 0.7\log_{10}\mathrm{DUR}).\mathrm{DUR}^{-0.48} + 0.0008\,(\mathrm{AREA})^{0.51}.\mathrm{DUR}^{0.4}.(0.3 + \log_{10}(\mathrm{AEP})) \qquad \text{..........}\,(4.6)$$

Coefficient of determination (R^2) = 0.994

Standard error = 0.0046

= 0.52% (as a % of the mean ARF)

In general, Eq. 4.6 appears to fit the sample mean values satisfactorily. However, it was felt that the variation of ARF with AEP estimated by the fitted relationship was slightly inconsistent for smaller catchment areas. This was attributed to the very small variation of sample ARF values with AEP for 250 and 500 km^2 catchment sizes. A slight adjustment to the exponent of the AREA term was therefore made and the relationship then refitted (Eq. 4.7). The fitted curves for 24, 48 and 72 hour durations together with sample mean values of ARF are shown in Figure 4.5.

$$\mathrm{ARF}_{\mathrm{AEP}} = 1.00 - 0.4\,(\mathrm{AREA}^{0.14} - 0.7\log_{10}\mathrm{DUR}).\mathrm{DUR}^{-0.48} + 0.0002\,(\mathrm{AREA})^{0.4}.\mathrm{DUR}^{0.41}.(0.3 + \log_{10}(\mathrm{AEP})) \quad \text{...........}\ (4.7)$$

Coefficient of determination (R^2) = 0.992
Standard error = 0.0052
= 0.58% (as a % of the mean ARF)

Range of application : $1\ \mathrm{km}^2 \leq \text{Area} \leq 10{,}000\ \mathrm{km}^2$
$0.50 \leq \text{AEP} \leq 0.0005$ (1 in 2000)
18 hours $\leq$ Duration ≤ 120 hours

Figure 4.5 shows a very good fit to the sample mean ARF values; in particular, the variation between the ARF and AEP is well represented. Figure 4.6 presents plots of residuals of ARF (derived minus predicted) against area, AEP and duration. The maximum residuals are in the order of 0.015, ie. about 2% of the computed ARF values. A comparison plot of derived mean ARFs against fitted values is shown in Figure 4.7. The above figures show a good agreement between the derived and predicted values without significant biases. Importantly the relationship is also well behaved in the extrapolated range of areas, durations and AEPs. Section 4.4 examines the performance of the relationship in the extreme range of AEPs.

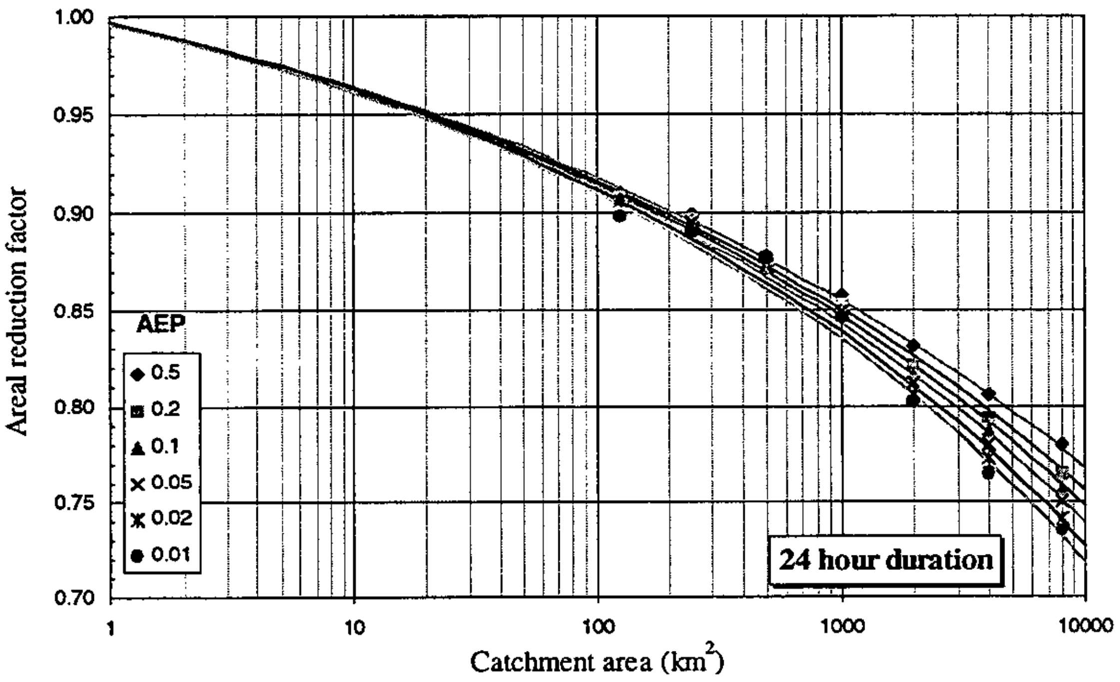
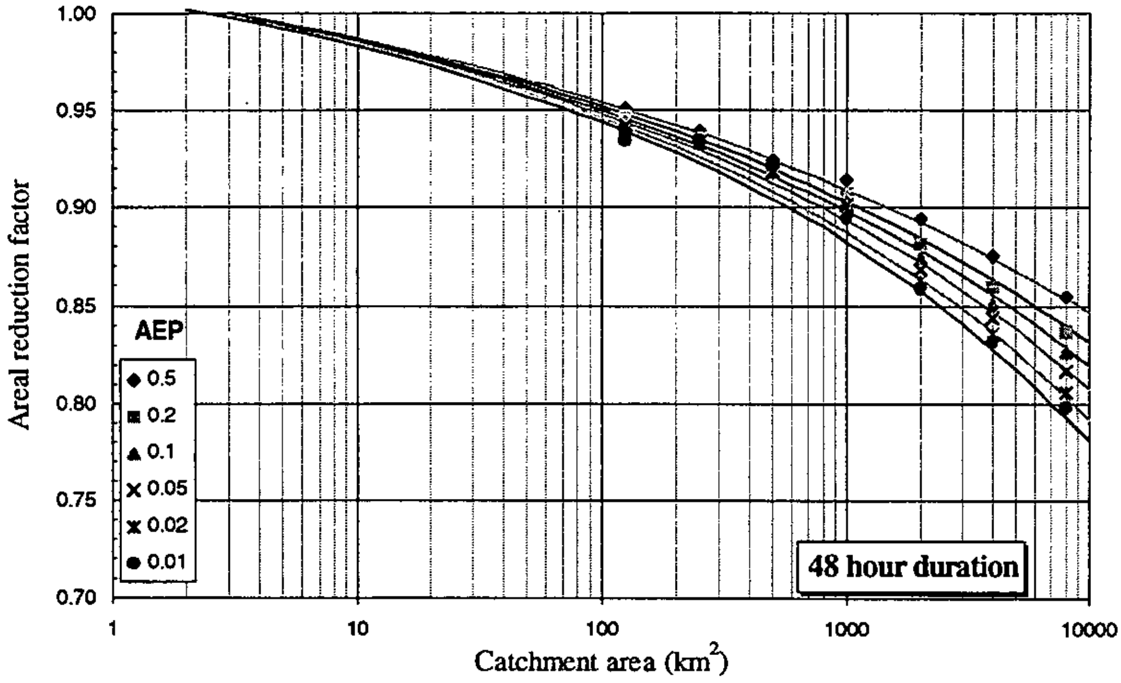


Figure 4.5 : Adopted curves for areal reduction factors (Eq. 4.7)



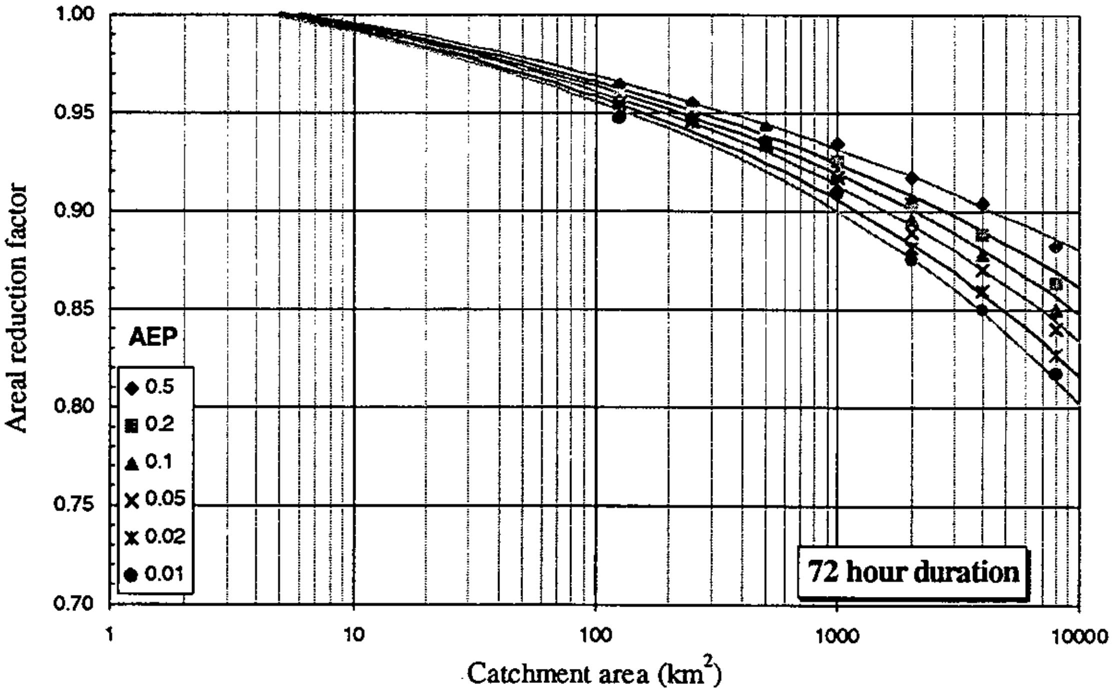


Figure 4.5 : Adopted curves for areal reduction factors (Eq. 4.7)

The uncertainty associated with the ARFs determined from the established relationship (Eq. 4.7) is twofold : sampling variability associated with the derivation of the ARFs from the sample catchments, and inaccuracies in the fitted relationship. From Figure 4.4, it can be observed that, in general, the fitted curves lie within the 95% confidence interval of the sample mean, thus confirming that the appropriateness of the adopted relationship.

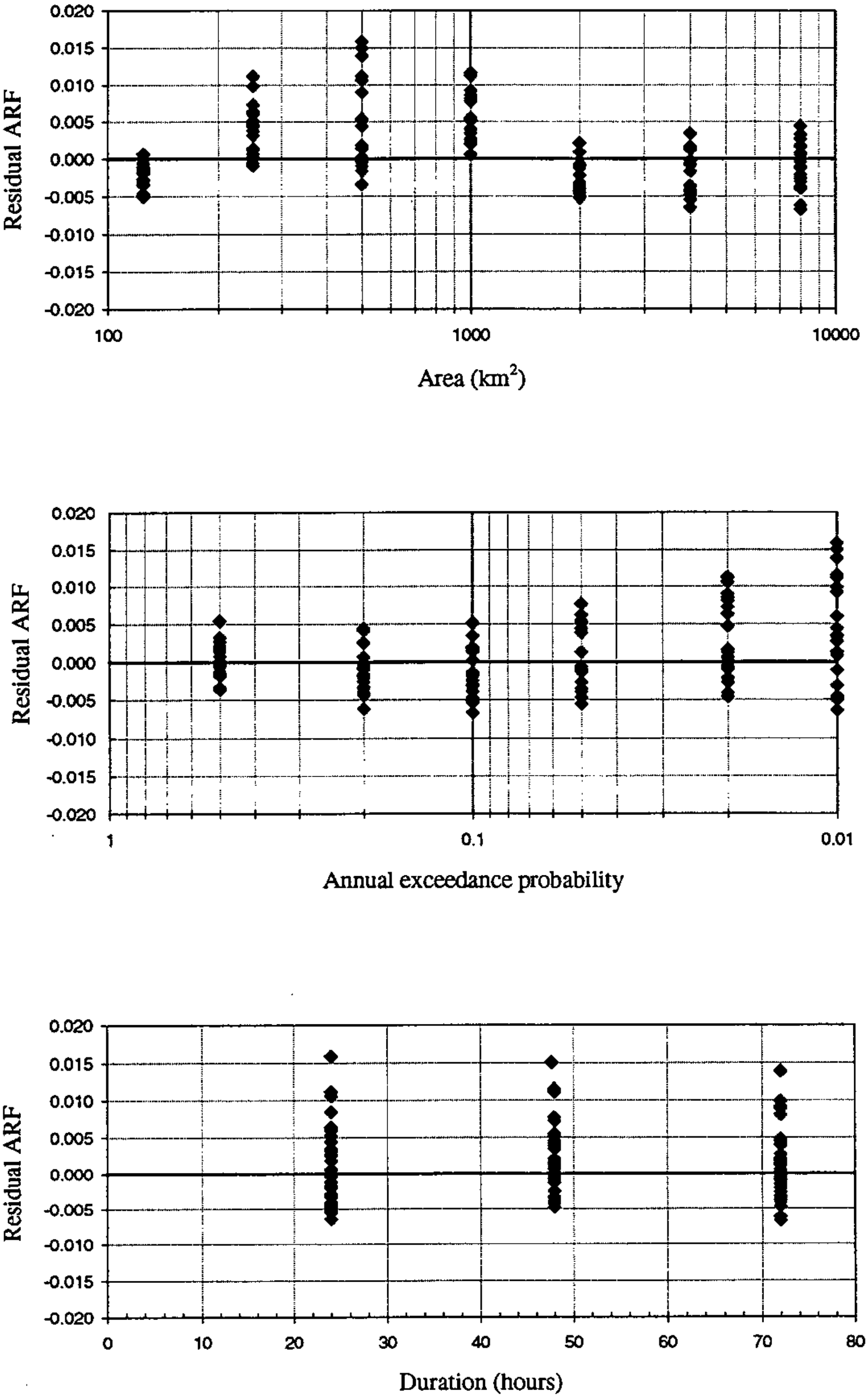
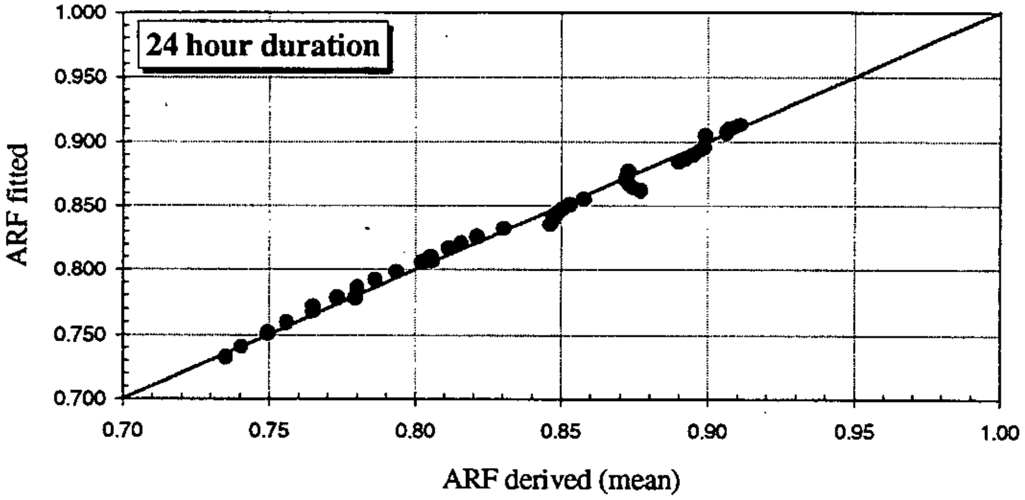
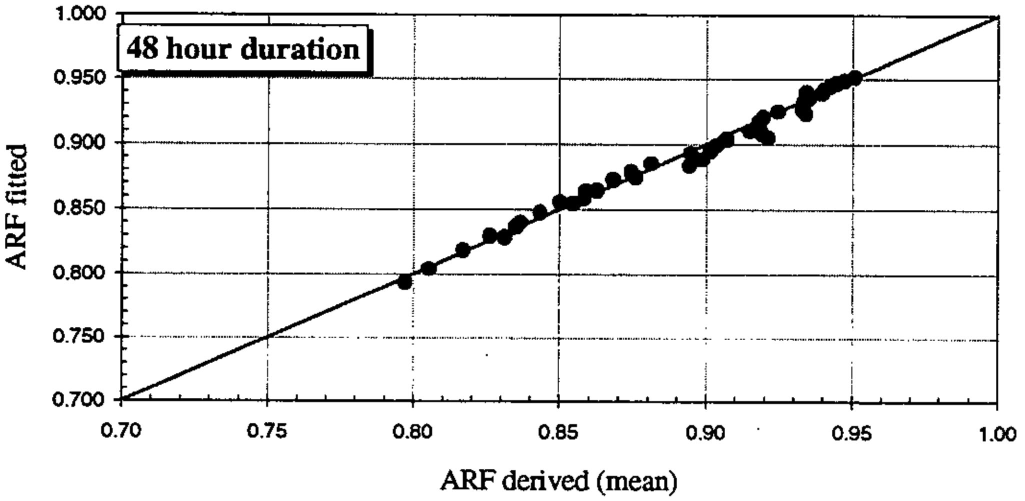


Figure 4.6 : Residual plots of areal reduction factors





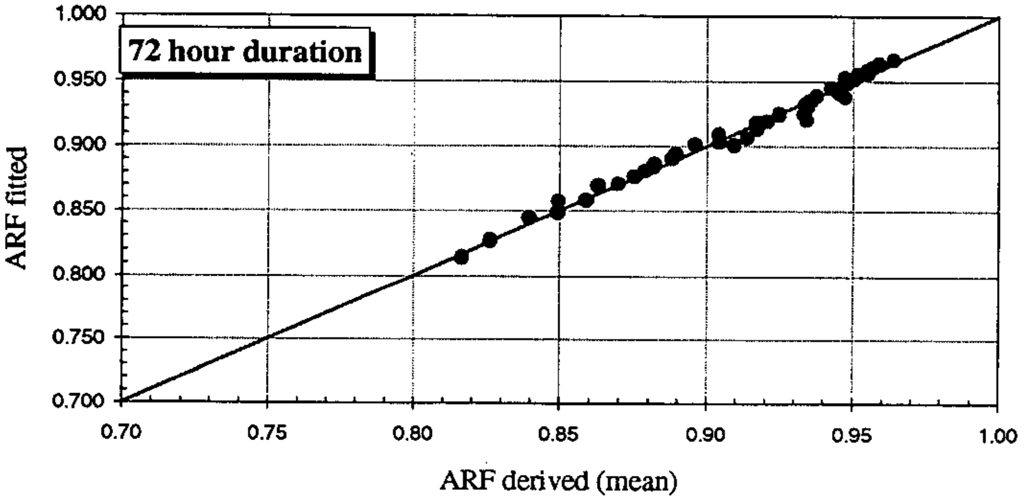


Figure 4.7 : Comparison plot of derived (mean) areal reduction factors against fitted values

4.4 Variation of areal reduction factors with AEP

In this study, the derivation of ARFs was based on analysis of daily rainfall data of appreciably long records, including a large number of stations with lengths of record greater than 100 years. Moreover, sample mean ARF values of a large number of 'catchments' were used in the derivation of the relationship for ARFs shown in Figure 4.5. This figure shows that the overall fit to the sample mean ARF values is good over the full range of AEPs analysed, justifying the assumption of a linear relationship between the ARF and the logarithms of AEP. The above factors lead to a conclusion that the derived ARFs to an AEP of 1% are quite reliable. The intention of this section is to justify the applicability of the results to extreme rainfalls, possibly to an AEP of 0.05%, based upon satisfactory confirmation with available evidence at probabilities lower than those considered in the initial analysis.

An additional analysis was carried out to estimate ARF values for an AEP of 1 in 1000 (0.1%) for the catchment size of 8000 km^2 using 30 sample catchments, and based on the same methodology as adopted previously. Figure 4.8 is a plot of ARF against AEP (on log scale) for three catchment sizes of 100, 1000, 8000 km^2 for durations of 24, 48 and 72 hours, supplemented by the estimated ARF values for an AEP of 0.1%. Given the uncertainty associated with the estimate for an AEP of 0.1%, it can be concluded that this estimate confirms satisfactorily the trend of the adopted relationship between ARF and AEP (Eq. 4.7).

Although it is not intended to extrapolate the results to the notional AEP of the Probable Maximum Precipitation (10^{-6}), it may be worthwhile to examine how well the extrapolated curves shown in Figure 4.8 compare with the extreme ARF values implied by the depth-duration-area (DDA) curves used for PMP estimation. If the DDA curves are assumed to represent rainfall estimates of equal AEP for different areas, then the ratio between the rainfall estimates for a given catchment size and a very small catchment (eg. 1 km^2) can be regarded as equivalent to an extreme areal reduction factor for that catchment size. The implied extreme areal reduction factors derived from envelope curves representing the maximum convergence rainfall at standard dew point conditions for the Generalised South-east Area Method (GSAM) - Coastal Region are given in Table 4.3 (Taylor, 1996).

Table 4.3 : Implied extreme areal reduction factors from the PMP estimates (Taylor, 1996)

Duration	Catchment size (km^2)					
(hours)	1	10	100	1000	10,000	100,000
24	1.00	0.936	0.851	0.688	0.444	0.120
48	1.00	0.936	0.853	0.705	0.492	0.158
72	1.00	0.934	0.865	0.782	0.559	0.170

These extreme areal reduction factors were assigned a notional AEP of 10^{-6} and plotted on Figure 4.8 to compare with the relationship established in this study. This plot provides confirmation that the assumed tendency for ARFs to reduce with reducing AEP also applies in the range of extreme rainfalls. However, for the reasons discussed in Siriwardena and Weinmann (1996), this information is only of a qualitative nature and the curves have therefore only been extrapolated to a lower AEP limit of 1 in 2000 (0.05%).

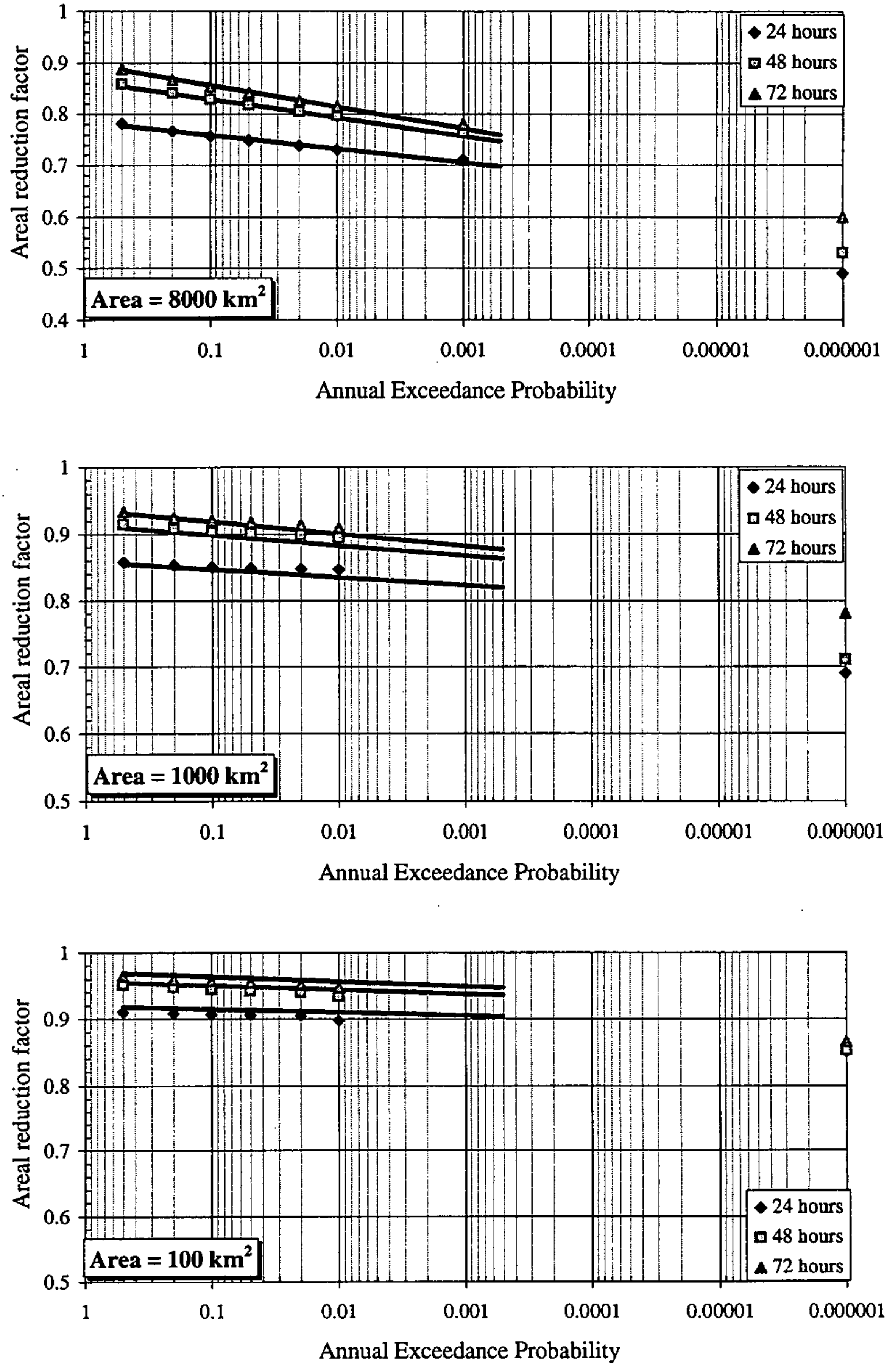


Figure 4.8 : Variation of areal reduction factor with AEP, including PMP estimates
(thick lines indicate relationships given by Eq. 4.7)

5. COMPARISON OF RESULTS WITH PREVIOUS STUDIES

This chapter gives comparisons of the areal reduction factors (ARFs) derived in this study with those of other researchers using Australian data (Avery, 1991; Nittim, 1993; Masters, 1993; Masters and Irish, 1994; Meynink and Brady, 1993; Porter and Ladson, 1993). It was also considered appropriate to compare the results with broadscale studies conducted outside Australia including the basic work on which ARR87 is based, the UK Flood Studies Report (NERC, 1975), and a study for a region in the UK by Stewart (1989) employing a similar methodology as used in this study. The relationship between ARFs and AEP determined in this study is also reviewed with respect to the findings of other researchers.

5.1 Comparison of the results with studies based on Australian data

In recent times, a number of studies have been carried out in Australia to derive ARFs for different parts of the country, but mainly for the south-eastern coastal region. In general, they fall under the classification of fixed-area areal reduction factors based on empirical and analytical methods. Bell's method (Avery, 1991; Porter and Ladson, 1993; Nittim, 1989), methods based on Rodriguez-Iturbe and Mejia (1974) (Masters, 1993; Omolayo, 1993) and Myers and Zehr (1980) method (Masters, 1993) have been used to derive ARFs using annual maximum rainfall series. Omolayo (1995) adopted a partial series model to evaluate ARFs.

Avery (1991), Porter and Ladson (1993) and Nittim (1989) applied a variant of the method proposed by Bell (1976) to derive probabilistic estimates of ARFs. In applying this procedure, point rainfall estimates were obtained for a range of AEPs from the IFD curves given in Chapter 2 of ARR87. An average point IFD value for the catchment was then obtained by applying Thiessen weights at a number of points in the catchment. The areal rainfall estimates at the desired AEPs were obtained by fitting either a log-normal distribution or a log-Pearson III distribution to annual maximum areal rainfall series for durations from one to three days. These estimates were then converted to 'unrestricted' values by applying a suitable factor to represent durations of 24, 48 and 72 hours. Areal reduction factors were calculated by dividing 'unrestricted' areal average rainfalls by the corresponding weighted average of point IFD values.

It was found that the ARFs obtained by Porter and Ladson (1993) for four catchments (414-1970 km^2) in the Deakin Main Drain region of northern Victoria are considerably lower (up to 15%) than the corresponding values obtained in this study, in particular the values for an AEP of 0.50. However, the ARFs obtained by Nittim (1989) for two catchments (360 - 600 km^2) in suburban Sydney are in broad agreement with the corresponding values obtained in this study for Victoria for all durations. ARFs obtained by Avery (1991) for the Tweed (650 km^2) and Bellinger (640 km^2) catchments in NSW are considerably lower (up to 15%) than the corresponding ARFs obtained in this study for Victoria, but the results for the larger Manning catchment (6560 km^2) are in reasonable agreement.

Masters (1993) obtained an ARF of 0.75 for 24-hour duration for an area of 2200 km^2 in Sydney, using the Rodriguez-Iturbe and Mejia method. This may be compared with the ARF of 0.83-0.80 for a range of AEPs from 1 in 2 to 1 in 100 for the same size of catchment, obtained in this study for Victoria.

Omolayo (1993) estimated the ARFs for six Australian capital cities by considering circular areas of 100, 200, 250, 500 and 1000 km^2 within each city for one-day rainfall. He used four methods, namely the US Weather Bureau (1957) method, a UK method (NERC, 1975), Bell's (1976) method and Rodriguez-Iturbe and Mejia's (1974) method. His values for ARFs based on US, UK and Bell's methods for Melbourne appear to be considerably higher than the corresponding average values obtained in this study for Victoria. In particular, ARFs obtained by Bell's method for Melbourne are in the range of 2-6% higher in comparison to the average values obtained in this study. However, those values are well within the 95% prediction interval of the derived ARFs for Victoria. It should also be noted that Omolayo's study considered only data from a total of nine rainfall stations in a catchment area of 1000 km^2, with considerably smaller numbers of stations for smaller catchment areas. These results are therefore only equivalent to a single data point of derived ARF values from the present study.

Omolayo (1995) presented a theoretical partial series model that expresses the ARF in terms of the recurrence interval and the size and shape of the catchment. He applied this model to 1-day rainfall data from six Australian capital cities to evaluate ARFs for a range of AEPs. The results indicated a strong dependence of the ARF on the AEP, in particular, for large areas. This tendency is high compared to the weak dependency found to exist with respect to AEP in this study. Again, the limited database used in Omolayo's work should be noted. The length of record at all the stations used in the study was 30 years, considerably shorter than the average length of record used in this study.

It needs to be emphasised here that the above studies have generally been based on more limited samples than the present study. It was found that the ARF values determined in the above studies are generally within the 95% prediction interval of the derived ARFs for Victoria. Allowing also for some differences in hydrometeorological characteristics of the study regions, it can be concluded that the results of this study are consistent with the results of earlier studies using Australian data.

5.2 Comparison of the results with broadscale studies outside Australia

The ARFs recommended in the *Australian Rainfall and Runoff (ARR87)* are based on the application of the method developed by Myers and Zehr (1980) with rainfall data from the Chicago area in the United States. The set of curves given in Figure 2.6 of ARR87 has been recommended to derive ARFs up to a catchment area of 1000 km^2 and a duration of 24 hours.

The ARFs given in the Flood Studies Report (NERC, 1975) are based on analyses of annual maximum areal rainfall and the corresponding point rainfall on the day the annual maximum occurs (Section 2.2.2). Based on a nation-wide study of UK rainfall records, the composite diagram given in the Flood Studies Report (FSR) provides ARFs up to a catchment area of 10,000 km^2 and a duration of 192 hours (Figure 2.1). Neither FSR nor ARR87 considered the possible relationship of ARFs with AEP.

Comparison of the results of this study with those by Stewart (1989) for a limited region in the UK is of importance as the methodology adopted in deriving ARFs in the two studies is somewhat similar (Section 2.3.2). Based on daily rainfall data for North-West England, Stewart (1989) derived probabilistic estimates of ARFs for catchment areas ranging from 25 km^2 to 10,000 km^2 and for durations of 1 to 8 days.

Table 5.1 and Figure 5.1 compare the ARFs derived in this study with those given in ARR87, the Flood Studies Report and by Stewart (1989).

Table 5.1 : Comparison of ARFs of this study with recommended values in ARR87 and UK Flood Studies Report

Area (km^2)	Areal reduction factors (24-hour duration)								
	ARR87		FSR	This study : AEP from 0.50 to 0.01					
	Fig 2.6	Fig. 2.7		0.50	0.20	0.10	0.05	0.02	0.01
50	0.985	0.92	0.96	0.93	0.93	0.93	0.93	0.93	0.93
125	0.965	0.88	0.94	0.91	0.91	0.91	0.91	0.91	0.90
250	0.945	0.86	0.92	0.90	0.89	0.89	0.89	0.89	0.88
500	0.925	0.83	0.91	0.88	0.87	0.87	0.87	0.86	0.86
1000	0.915	0.81	0.89	0.86	0.85	0.85	0.84	0.84	0.84
2000	-	-	0.87	0.83	0.83	0.82	0.82	0.81	0.81
4000	-	-	0.86	0.81	0.80	0.79	0.79	0.78	0.77
8000	-	-	0.84	0.78	0.77	0.76	0.75	0.74	0.73

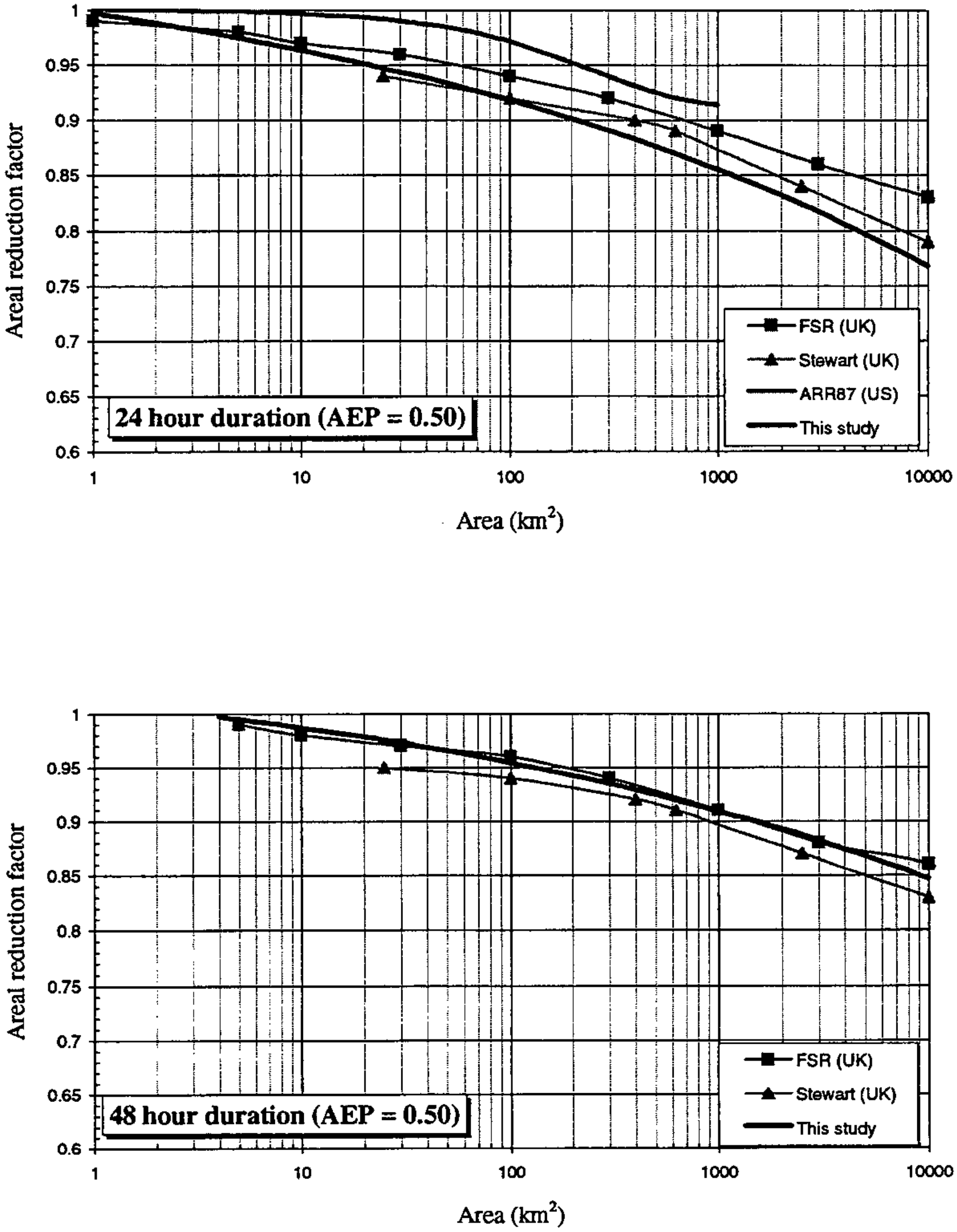
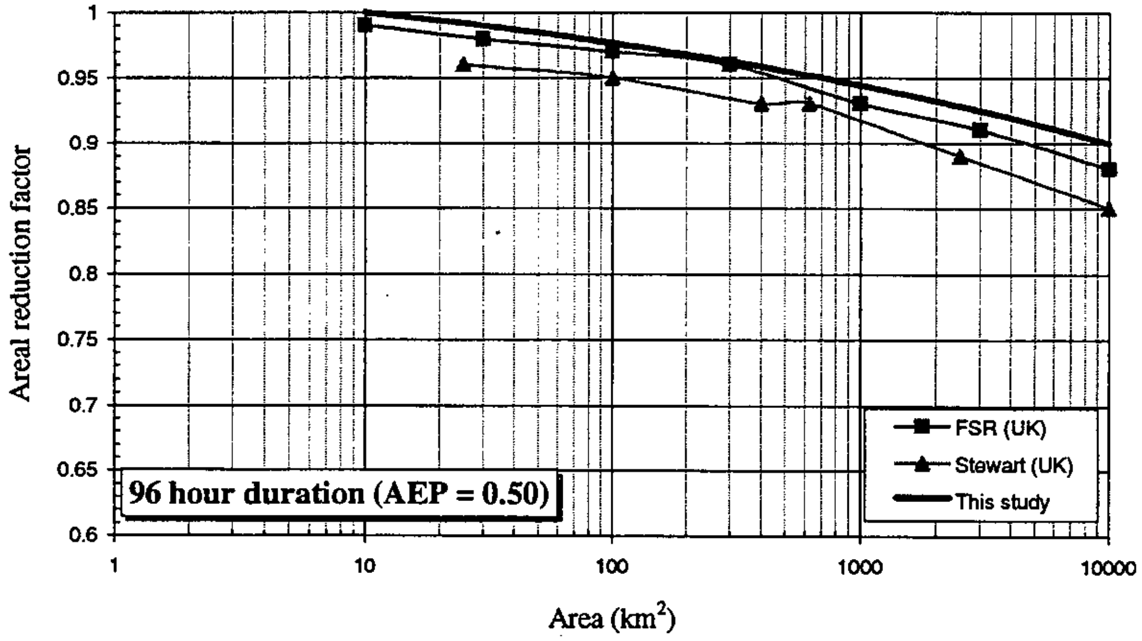


Figure 5.1 : Comparison of results with broadscale studies in UK and USA
(a) 24 and 48 hour durations



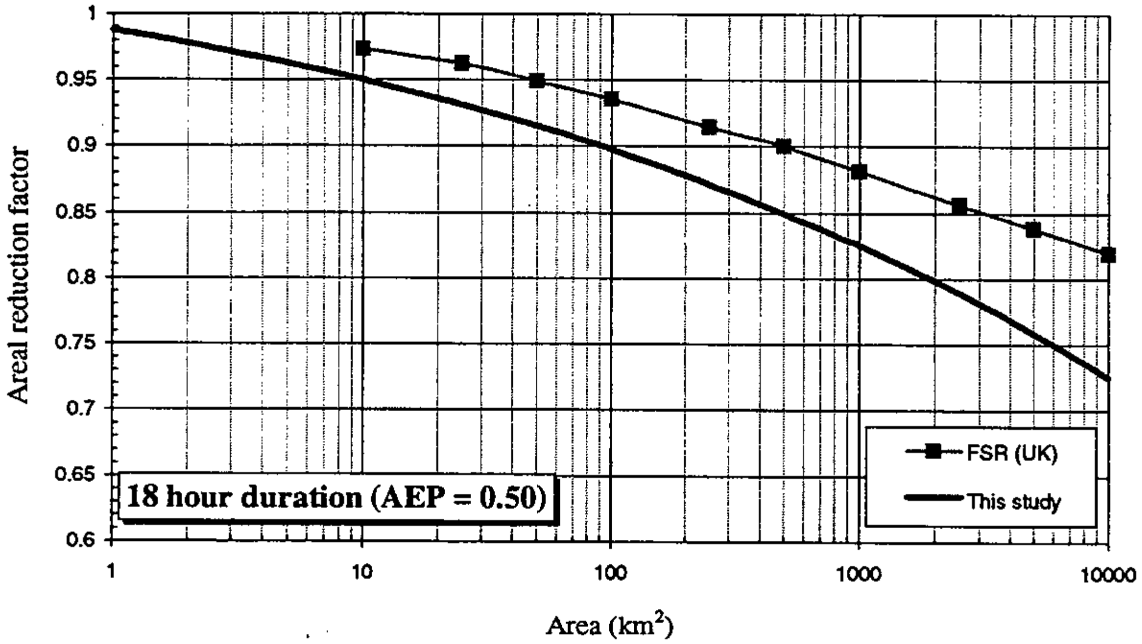


Figure 5.1 : Comparison of results with broadscale studies in UK and USA
(b) Extrapolation to 96 and 18 hour durations

The average ARFs (not dependent on AEP) given in ARR87 and FSR may be compared with ARFs which correspond to an AEP of 0.50 in this study. It can be concluded that the ARFs given in ARR87 for 24-hour duration and up to an area of 1000 km^2 are 5-6% higher than the corresponding values from this study. For an AEP of 0.01 (1 in 100), the ARFs given in ARR87 are 6-8% higher than those recommended from this study.

The ARFs given in FSR for 48 and 96-hour durations are acceptably close (difference less than 1%) to the ARFs from this study for an AEP of 0.50 and over a range of catchment areas from 10 km^2 to 1000 km^2. For a 24-hour duration, the ARFs given in FSR are 1-4% higher over the same range of catchment areas, showing a larger discrepancy as the area increases. The corresponding difference for 18 hour duration is in the range of 2-6% and increases further as the area increases. For a catchment area of 10,000 km^2, the ARFs given in FSR for durations of 24 and 18 hours are about 7% and 13% higher than those of this study.

The ARFs derived by Stewart (1989) for 48 and 96-hour durations (for AEP of 0.50) are marginally lower than those from this study, over a range of catchment areas from 25 km^2 to 10,000 km^2. For the 24-hour duration, there is no significant difference between the two sets of values up to about 100 km^2, but for larger catchment areas the ARFs derived by Stewart (1989) are about 2% higher.

It can be concluded that the ARFs of this study are in broad agreement with those from the Flood Studies Report and Stewart (1989). An exception are the ARFs for relatively short durations (18-24 hours) and large areas (1000 km^2 to 10,000 km^2) for which FSR values were found to be appreciably larger (up to 13%) than those from this study. The effect of duration on the areal reduction factor was shown to be more significant (Figure 5.1) in this study than in the other studies. The differences in the results probably reflect different meteorological conditions in the two regions, as well as differences in the data sets available for the studies. The study by Stewart had only one sample available for a catchment size of 10,000 km^2.

5.3 Relationship between areal reduction factors and AEP

The relationship between ARFs and AEP was tested by a number of researchers for Australian data using variations of Bell's procedure. Nittim (1989) failed to establish a consistent trend for the two catchments analysed in NSW. Avery (1989) observed a slight tendency for the ARF to increase with decreasing AEP for the three catchments analysed. Based on four catchments, Porter and Ladson (1993) observed that the ARF values increased with decreasing AEP but appeared to remain approximately constant for any AEP less than 0.10. Failure to detect consistent patterns may be attributed to the limited number of samples used in the above analyses, the limitations of the methodology employed or the weakness of any relationship present.

Bell (1976), Stewart (1989) and Omolayo (1995) observed a tendency of areal reduction factors to reduce with decreasing AEP. The relationship between ARF and AEP found by these researchers is compared in Figure 5.2 with that of this study for a catchment area of 1000 km^2 and a duration of 24 hours. This study has confirmed the tendency for ARF values to diminish with decreasing AEP, as reported by others, but the degree of reduction was found to be less than in the other studies. The tendency is more pronounced for larger catchment areas (eg. greater than 1000 km^2). This was also confirmed by the results of Stewart (1989). In interpreting these results, the limitations of the data set used by Omolayo (1995) should be kept in mind.

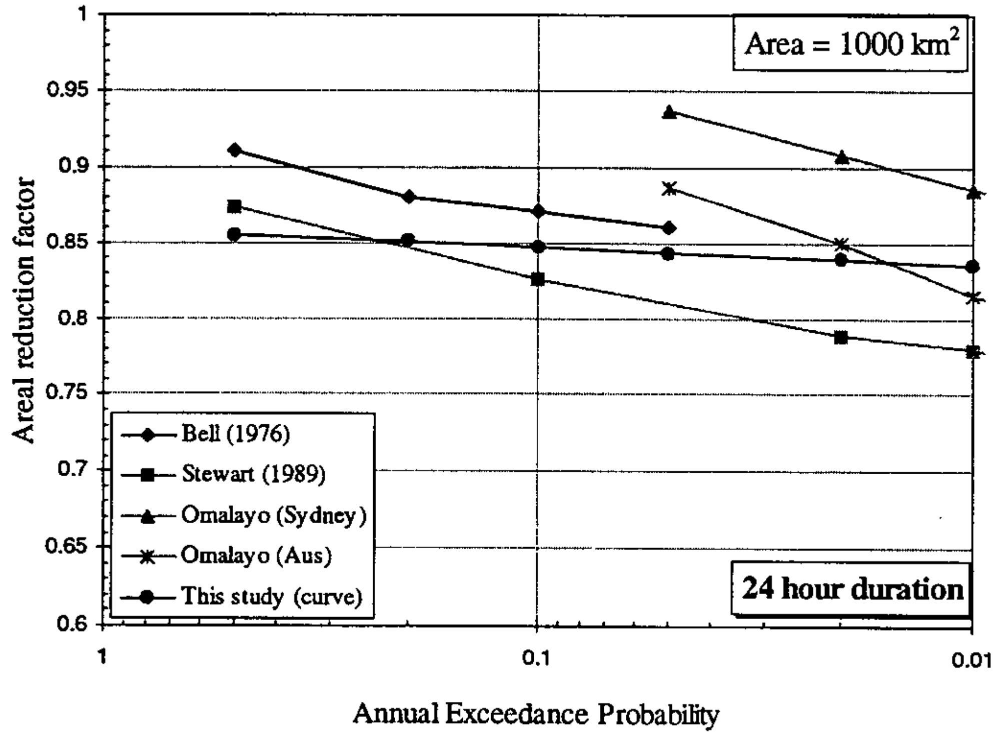


Figure 5.2 : Relationship between areal reduction factors and AEP

6. CONCLUSION

6.1 Summary

Design rainfall information for flood estimation is generally made available to designers in the form of *point rainfall intensities* (eg. the rainfall intensity-frequency-duration information given in "Australian Rainfall and Runoff", I. E. Aust., 1987). 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 (or ARI), 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 over the whole of the catchment area.

ARF values for a catchment of a given size can be determined from the analysis of rainfall data available at the gauges within that catchment. This requires separate frequency analysis of extreme values of point rainfall and areal rainfall for selected durations. The determination of average ARF values for a whole region requires the repetition of this procedure for many different catchments of that size.

The ARF values presented in this report are based on a detailed analyses using daily rainfall data from over 2000 rain gauges in Victoria. The methodology used is a modified version of Bell's method (Bell, 1976) and was selected on the basis of an extensive literature survey (Srikanthan, 1995). The adoption of the final method followed extensive evaluation of variations in procedural steps.

Individual ARF values were computed for a large number of circular "sample catchments" of selected size, distributed over those parts of Victoria with a relatively high rain gauge density. The average *point rainfall frequency curve* for each sample was determined using a regional L-moment approach for the Generalised Extreme Value (GEV) distribution (Hosking, 1990). Average areal rainfalls for the catchment were computed using Thiessen weights, and the *areal rainfall frequency curve* was also fitted by the method of L-moments using a GEV distribution. Sets of ARF values were computed for durations of 1, 2 and 3 days, catchment areas of 125, 250, 500, 1000, 2000, 4000 and 8000 km^2, and for AEPs of 1 in 2, 5, 10, 20, 50 and 100 years.

6.2 Conclusion

The main outcomes of this work are :

- The results of this research can be expressed by the following relationship for areal reduction factor (ARF) as a function of rainfall duration (DUR), catchment area (AREA) and annual exceedance probability (AEP).

  $$\mathrm{ARF}_{\mathrm{AEP}} = 1.00 - 0.4\,(\mathrm{AREA}^{0.14} - 0.7\log_{10}\mathrm{DUR}).\mathrm{DUR}^{-0.48} + 0.0002\,(\mathrm{AREA})^{0.4}.\mathrm{DUR}^{0.41}.(0.3 + \log_{10}(\mathrm{AEP}))$$

  Range of application : $1\ \mathrm{km}^2 \leq \mathrm{AREA} \leq 10{,}000\ \mathrm{km}^2$
  $0.50 \leq \mathrm{AEP} \leq 0.0005$
  $18\ \mathrm{h} \leq \mathrm{DUR} \leq 120\ \mathrm{h}$

- It was shown that the ARFs derived in this study for 24-hour duration and up to an area of 1000 km^2 are 5-8% lower than the corresponding values given in ARR87 (IEAust, 1987), but generally similar to ARF values determined for UK catchments.

- The study identified small but statistically significant differences in ARF values for different parts of Victoria, in particular the southern coastal regions, probably reflecting differences in hydrometeorological factors such as typical storm sizes. However, there is at present insufficient information to allow differentiation of design values within Victoria based on catchment location.

- It is recommended that the ARF values derived in this study for rainfall durations from 18 hours to 120 hours replace the values in ARR87 for design flood studies of catchments in Victoria and in regions with similar hydrometeorological characteristics.

- Although the determination of ARFs for durations less than 18 hours did not form part of this study, practitioners will need some guidance on appropriate ARF values in the interim, until more specific results based on Australian data become available. Appendix C provides details of a proposed method to estimate *interim* ARF values for durations between 1 hour and 18 hours.

6.3 Recommendations for future studies

It is considered desirable to replace the areal reduction factors given in ARR87 for application in different parts of Australia by a set of values derived from the analysis of Australian rainfall data. On this basis, the following recommendations are made for future studies :

- The modified Bell's method used in this study (with further modifications, if necessary) should be applied to derive ARFs for those regions in other states of Australia, which have an adequate rainfall station network.

- Areal reduction factors for durations less than 24 hours should be derived using an appropriate technique which takes account of the more limited availability of pluviograph data. Such a study is proposed for Victoria, as part of a future project of the CRC for Catchment Hydrology. Areal reduction factors over the whole range of durations of interest would then be available for Victoria.

- It would also 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. In accordance with recommendations by Srikanthan (1995), the Rodriguez-Iturbe and Mejia (1974) method would be suitable for such an evaluation.

- The investigation of the regional variability of areal reduction factors and the meteorological factors responsible for any variations should be continued by including the results from other States when they become available.

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APPENDIX A

INTERIM AREAL REDUCTION FACTORS FOR DURATIONS LESS THAN 18 HOURS

APPENDIX A

INTERIM AREAL REDUCTION FACTORS FOR DURATIONS LESS THAN 18 HOURS

A.1 Introduction

The objective of the study summarised in the body of this report was limited to determining areal reduction factor (ARF) values for rainfall durations in the range from 18 to 120 hours, based on the analysis of *daily rainfall data* for the whole State of Victoria. However, the study produced ARF values for longer duration rainfalls which differ so significantly from the currently recommended values in ARR87 that it would be difficult, and probably inappropriate, to use the two sets of values in a complementary fashion. This problem is illustrated in Figure A.1, which superimposes the new ARF curves for 18 and 24 hours duration onto the currently used ARF curves from ARR87. It shows clearly that the proposed new ARF curve for 18 hours duration falls below the currently used ARF values for 3 hours duration over most of the range of catchment areas.

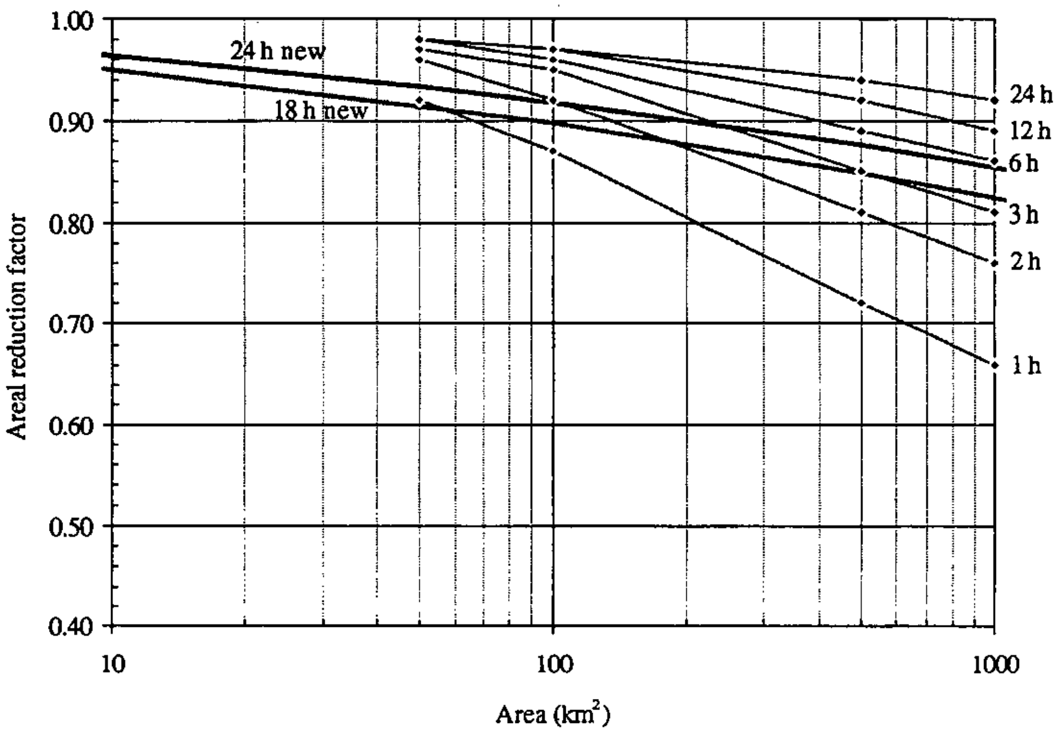

Figure A.1 : Comparison of new ARF curves with ARF values given in ARR87

In the longer term, revised values of short duration ARFs will need to be based on a detailed analysis of Victorian pluviograph data. However, in the interim period, until the results of such a detailed study become available, a set of recommendations is required to allow practitioners to make the best use of the new ARF values, without any gross inconsistencies in the transition region between long duration and short duration rainfalls. The purpose of this Appendix is the development of a set of interim ARFs for durations less than 18 hours.

A.2 Derivation of ARF values for short durations

Determination of ARF values for rainfall durations of less than 24 hours by a similar methodology as employed for the longer duration ARFs (ie. a modified Bell's method) would require a substantial database of pluviograph data. Such data is only available at the required network density in a few isolated regions of Victoria, eg. the Melbourne metropolitan area and the area around the Upper Thomson River catchment. Given the different sources of the data, it is also expected that some of this data would require considerable processing before it could be used in an analysis of areal reduction factors. The lack of data over a more extended region makes it desirable to develop a methodology that is based on a theoretical model of the spatial rainfall process. Such models have been proposed in the literature but would need to be assessed for their suitability with Victorian rainfall conditions. The compilation of the required database of Victorian pluviograph data, the development/testing of improved methodology and its application to derive short duration ARF values for Victoria are outside the scope of the present study within CRCCH Project D3, but are proposed to form part of a future CRCCH project.

In this situation, where no specific data on short duration ARF values for Victoria are available, the derivation of interim ARF values for short durations needs to be based on published results of ARF studies for other Australian or overseas regions, perhaps with limited extrapolation of the new long duration ARF results.

There are only two known studies of ARF values for short durations based on Australian data: Omolayo (1993, 1995), and Masters and Irish (1994). Neither of these studies has been comprehensive enough to provide a basis for estimating ARF values for the full range of durations and catchment sizes of interest in design applications. The most relevant overseas studies are by the U.S. National Weather Service (1980), providing the basis for the currently adopted ARF values in Australia, and by the U.K. Institute of Hydrology, providing the basis for the ARF values in the U.K. Flood Studies Report (NERC 1975).

The comparison of 24 hour ARF values in Figure 5.1 (a) of the main report indicates that the results of the CRCCH study for Victoria are slightly lower than the corresponding values recommended in the U.K. Flood Studies Report, but considerably lower than the values in ARR87 (based on U.S. data). In Figure A.2 the proposed new ARF curves for durations of 18 to 48 hours are plotted together with the 1 hour duration curves from

ARR87 and from the U.K. Flood Studies Report. This graph illustrates clearly that the U.K. curves for short durations are more consistent with the new ARF curves for long durations than the ARR87 curves.

On this basis, it seems more appropriate to base the estimation of interim values of short duration ARFs on the U.K. data. The procedure adopted is an interpolation between the 18 hour value obtained in the CRCCH study and the 1 hour value from the U.K. Flood Studies Report.

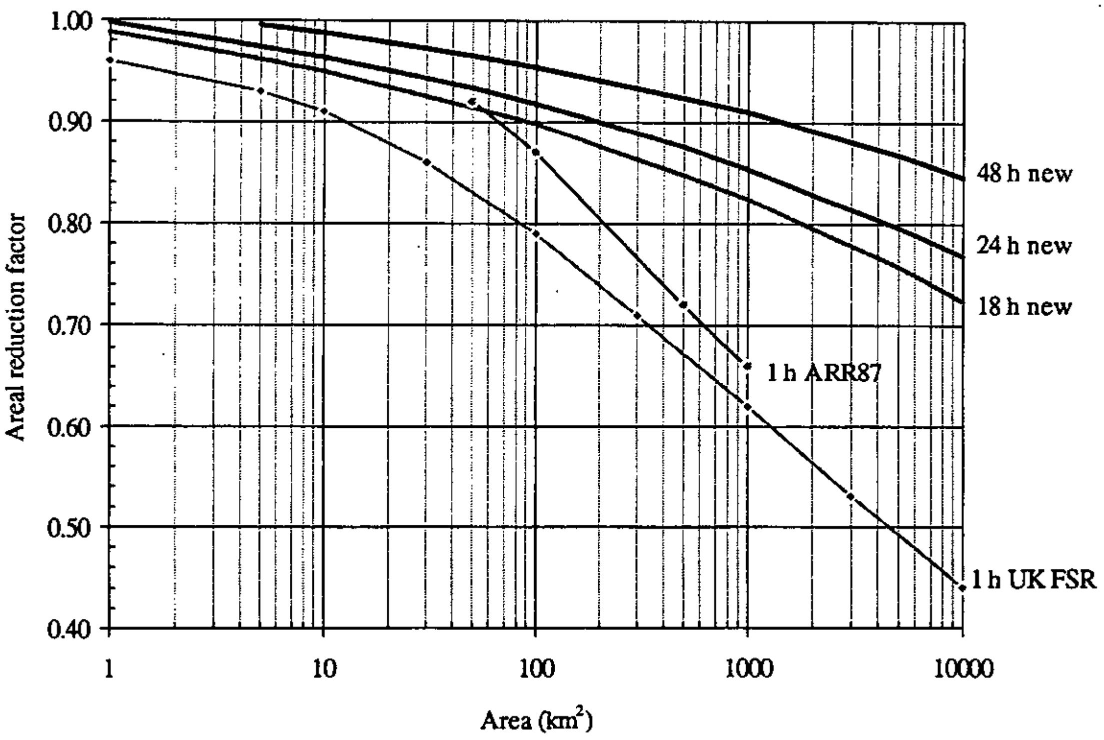

Figure A.2 : Consistency of long and short duration ARF values

A.3 Fitting curves for short duration ARF values

The objective of the curve fitting was to find an 'interpolation rule' for ARF values between 1 hour and 18 hour duration that would be consistent with the implied relationship between the ARF curves for the 18 and 24 hour durations.

As the initial step, the derived ARFs for 18 and 24 hour durations from this study and ARF values given for 1 hour duration in the UK Flood Studies Report were fitted to a single non-linear relationship of the following form:

$$ARF_{0.50} = 1.00 - 0.10(AREA^{0.14} - 0.879) - 0.029 \cdot (AREA)^{0.233} \cdot (DUR)^{0.146} \cdot (1.255 - \log_{10} DUR)$$

$$1h \le DUR \le 24h$$

$R^2 = 0.994$; standard error = 0.011 (based on 18h, 24h, and 1h (FSR) data points)

The relationship between the ARF and duration implied by the above equation is shown in Figure A.3, as a plot of ARF against logarithm of duration. Figure A.4 shows the same relationship as deduced from the curves given in the U.K. Flood Studies Report. It can be concluded that the tendencies shown by the two curves are quite opposite (curving in opposite directions) but not deviating much from a linear relationship, in particular for small catchment sizes and durations up to 6 hours. As a compromise, a linear relationship between the ARF and the logarithm of duration was adopted to establish the following equation:

$$\mathrm{ARF}_{0.50} = 1.00 - 0.10(\mathrm{AREA}^{0.14} - 0.879) - 0.029 \cdot (\mathrm{AREA})^{0.233} \cdot (1.255 - \log_{10}\mathrm{DUR})$$

$$1\,\mathrm{h} \leq \mathrm{DUR} \leq 18\,\mathrm{h}$$

$R^2 = 0.992$; standard error = 0.013 (based on 18h and 1h (FSR) data points)

The fitted curves are shown in Figure A.5. This relationship was considered adequate for the estimation of interim values of short duration ARFs, keeping in mind the fact that the estimate for the 1 hour duration is based on overseas data and has not been tested using Victorian data.

The derived interim values of short duration ARFs are for an annual exceedance probability (AEP) of 1 in 2. For shorter duration rainfalls there is only a small variation of ARF with AEP and, given the degree of approximation involved in the derivation of the interim values, it is considered acceptable to apply the same ARF value to all AEPs.

A.4 Evaluation of proposed interim values

The comparison in Table A.1 of the proposed interim ARF values with the ARF values derived by Masters and Irish (1994) for a catchment area of 2200 km^2 in the Sydney region indicates that the proposed interim values for Victoria are probably conservatively high, even if some allowance is made for likely differences in ARF values for the two regions.

Table A.1: Comparison of proposed interim ARF values for Victoria with ARF values for Sydney (Masters and Irish, 1994; A = 2200 km^2).

Duration (hours)	Sydney ARF values	Victoria Interim ARF values	Difference (%)
1	0.31	0.57	+83
2	0.44	0.63	+43
3	0.52	0.66	+27
6	0.60	0.72	+20
12	0.70	0.76	+ 9
24	0.75	0.83*	+11

* ARF value from Equation 4.2

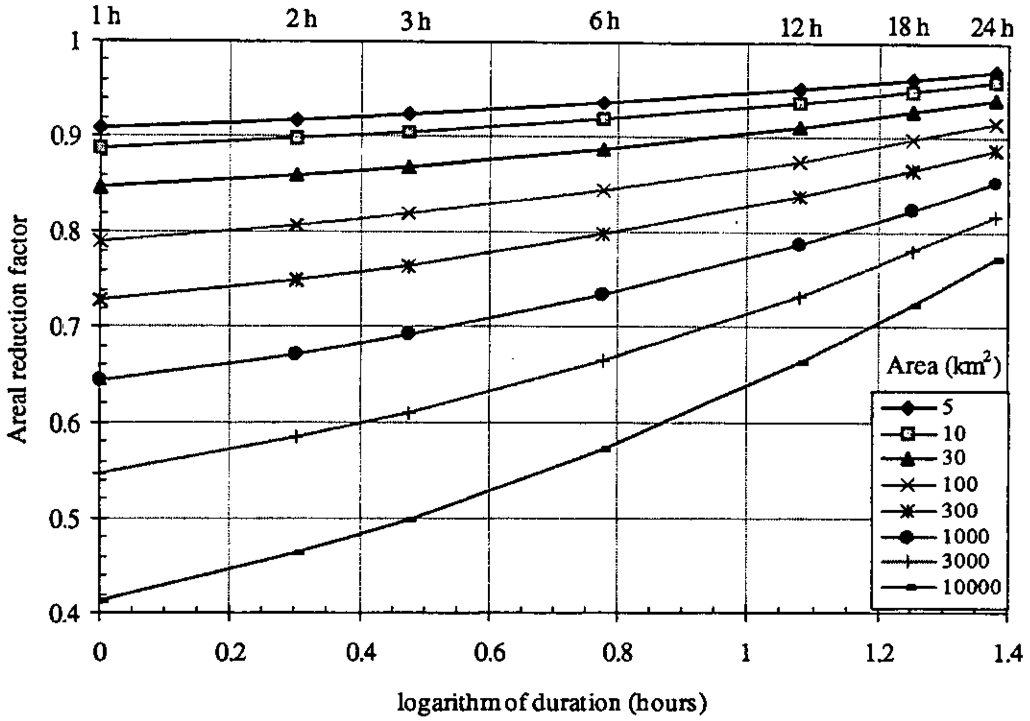

Figure A.3 : Relationship between ARF and duration based on trends of 18h and 24h ARF values

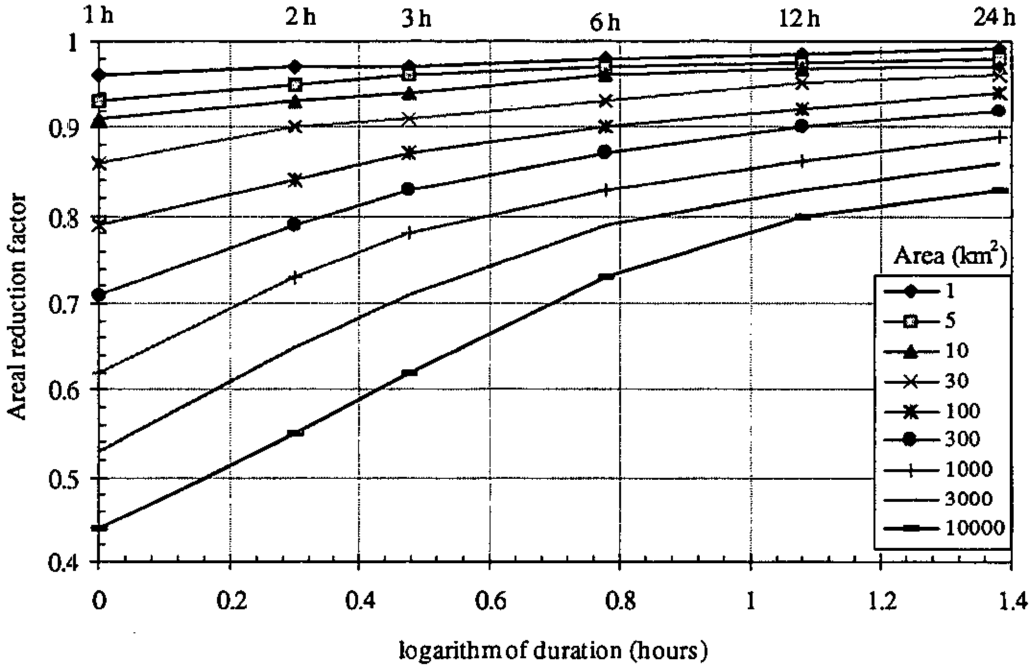

Figure A.4 : Relationship between ARF and duration deduced from UK Flood Studies Report

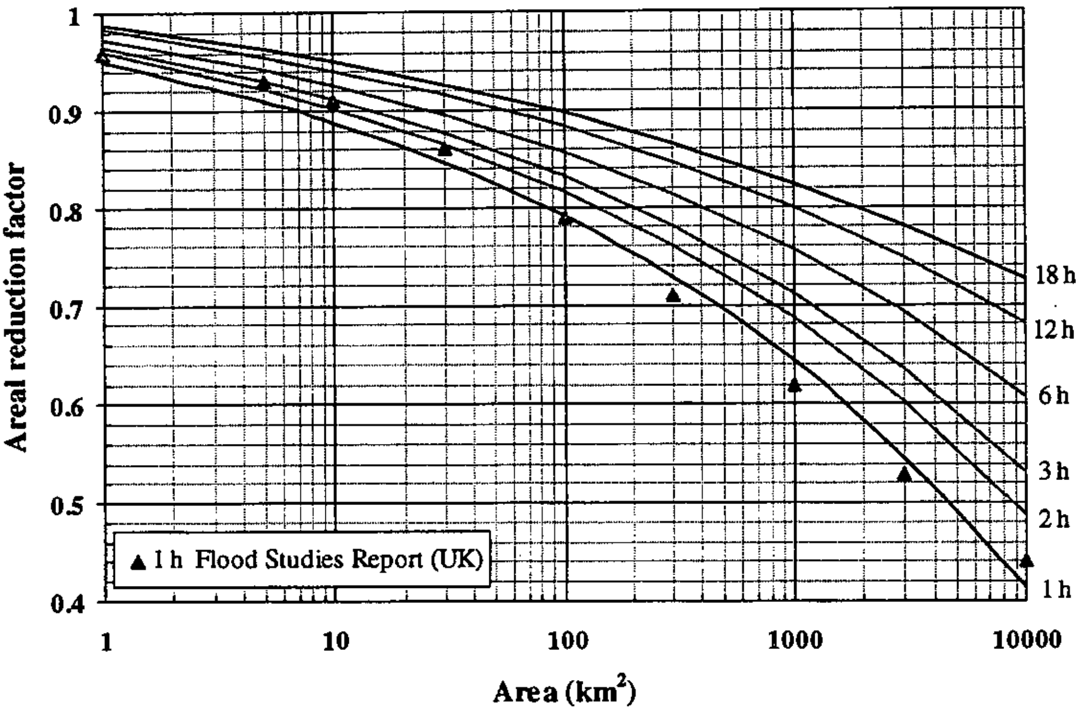

Figure A.5 : Proposed interim areal reduction factors for short durations (from 1h to 18h)

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Melbourne Water

Monash University

Murray-Darling Basin Commission

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