New Design Rainfalls for Australia

Janice Green
IFD Revision Project Director, Environment and Research Division, Bureau of Meteorology, Canberra, Australia

Catherine Beesley
Hydrologist, Environment and Research Division, Bureau of Meteorology, Melbourne, Australia

Cynthia The
Hydrologist, Environment and Research Division, Bureau of Meteorology, Sydney, Australia

Scott Podger
Hydrologist, Environment and Research Division, Bureau of Meteorology, Sydney, Australia

Design rainfall estimates are essential in the design of infrastructure such as gutters, roofs, culverts, stormwater drains, flood mitigation levees and retarding basins. They are used by engineers to determine the flood capacity and water level to meet required levels of safety. They are also integral to spillway adequacy assessments undertaken to determine the flood magnitude that existing dams can safely withstand. Other uses of design rainfalls include the assigning of a probability to an observed rainfall event and flood warning and emergency management.

The previous design rainfall estimates were derived by the Bureau of Meteorology (the Bureau) in the early 1980s using a database comprising primarily of Bureau raingauges and techniques for statistical data analysis that were considered appropriate at the time. They were provided for durations from 5 minutes to 72 hours (3 days) and for probabilities from the 1 year Average Recurrence Interval (ARI) to the 100 year ARI. More recently, estimates of rare design rainfall estimates for probabilities from 100 year ARI to 2000 year ARI have been derived for each state, using the CRCFORGE method. Design rainfalls for probabilities more frequent than 1 year ARI were not provided.

The Bureau has recently completed an 8 year project which has produced new design rainfall estimates. The new design rainfall estimates are based on a greatly expanded database which incorporates rainfall data collected by organisations across Australia. These data have been analysed using contemporary statistical methods that are appropriate for Australian rainfall data. The new design rainfalls are provided for durations from 1 minute to 168 hours (7 days) and for probabilities from 12 Exceedances per Year (or 1 month ARI) to 0.05 % Annual Exceedance Probability (or 2000 year ARI) and are available from the Bureau's website for any location in Australia.

1. INTRODUCTION

Design rainfall estimates are used in the design of infrastructure including gutters, roofs, culverts, stormwater drains, flood mitigation levees, retarding basins and dams. They are used by engineers to determine the flood capacity and water level to meet required levels of safety. They are also integral to large dam spillway adequacy assessments undertaken to determine the flood magnitude that existing dams can safely withstand. Other uses of design rainfalls include the assigning of a probability to an observed rainfall event and making decisions about flood warnings and emergency management.

There are five broad types of design rainfalls that are currently used for design purposes, generally categorised by probability. These are summarised below and presented graphically in Figure 1.

Probability	Occurrence	
12 EY to 1 EY	Very frequent	
1 EY to 10% AEP	Frequent	} IFDs
10% to 1% AEP	Infrequent	}
1% to 0.05% AEP	Rare	
Extreme	Extreme	

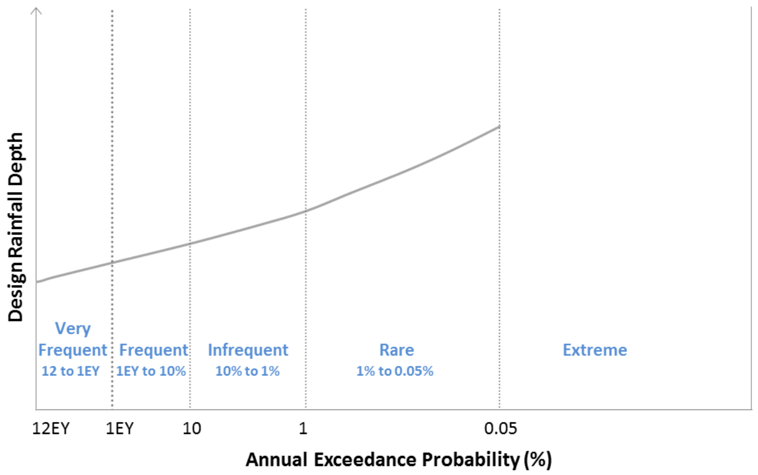

Figure 1 Types of design rainfall

The probability terminology adopted is the terminology proposed to be adopted for the 2015 edition of Australian Rainfall and Runoff (ARR2015) (Institution of Engineers, 1987). In this new terminology the following terms are adopted:

- Exceedances per Year (EY) are adopted for probabilities more frequent than or equal to the previous 1 year Average Recurrence Interval (ARI)
- Annual Exceedance Probability (AEP) expressed as a percentage is adopted for probabilities less frequent than 1 EY to 1% AEP.
- AEP expressed as 1 in x is adopted for probabilities less frequent than 1% AEP

Although the design flood standards for structures vary from state to state, broadly they can be categorised as shown in Table 1.

Table 1. Typical Design Probabilities

Infrastructure	Typical Range of AEPs
Water sensitive urban design (WSUD)	4 EY
Road reserves	50% to 10%
Gutters and pipes	20% to 10%
Stormwater drains	2% to 1%
Minor culverts	20% to 2%
Major culverts	2% to 1%
Flood mitigation	5% to 1%
Floodplain management	2% to 0.05%
Bridge design	0.05%
Dam spillways	1 in 10 000 to 1 in 10 000 000

This paper provides an overview of the suite of design rainfalls recently derived by the Bureau and which are available via the Bureau's website. The focus of this paper is on design rainfall estimates in the range from 12 EY used in WSUD to those with a probability of 0.05% used in bridge design and spillway adequacy assessment. The objective of this paper is to provide a summary of the complete range of new design rainfalls. In Section 2 a background to previous estimates of very frequent, frequent and infrequent, and rare design rainfalls is provided. Section 3 provides an overview of the approaches adopted to produce new design rainfalls in these categories and Section 4 presents how the new design rainfalls and other information can be obtained. Further details on the individual categories of design rainfalls can be found in the papers listed in Section 6.

2. BACKGROUND

In this section a history of the estimates of very frequent, frequent and infrequent; and rare design rainfalls is provided to identify the approaches that are now superseded by the new design rainfalls.

2.1 Very frequent design rainfalls

To date, design rainfalls for probabilities more frequent than 1 EY (or the corresponding one year ARI), which are used primarily in WSUD and some stormwater applications, have not been provided. Although values for 0.25 year ARI and 0.5 year ARI for durations from one minute to three days were available for a fee from the Bureau, these were only available for sites where rain gauges were located; were at-site values rather than regional, gridded values; and were inconsistent from site to site due to difference in the available length of records.

In the absence of specific estimates or advice, agencies responsible for ensuring compliance to the relevant guidelines have provided their own advice on the approach to be adopted for estimating very frequent design rainfalls and consequent design floods. In particular, many stormwater quality or WSUD guidelines recommend a flow threshold of Q_{3month} (or 4 EY) for the design of stormwater quality treatment devices. Table 2 summarises some of the approaches adopted for estimating Q_{3month}.

Table 2. Summary of Australian practice for estimating very frequent design rainfalls

Source	Guideline	Method
Hastings Council Stormwater Management	Design Storm equivalent to a 3 month ARI storm event	40% of 1 year ARI storm event
Parramatta City Council Stormwater Asset Plan	3 month ARI storm event	0.5 x Q_{1year} (flow)
South Australia Government	3 month design flows	Logarithmic extrapolation of design flows from AR&R87
NSW State Government Stormwater Source Control	3 month ARI rainfall event	25% x 1 year ARI (rainfall)
Gold Coast City Council	Factors applied to 1 in 1 year ARI	3 month ARI = 0.50 x 1:1 year ARI
Queensland Urban Drainage Manual 2013	0.5 x 63% AEP (1 in 1 year) to replace the 3 month ARI terminology	0.5 x 63% AEP
WSUD Technical Design Guidelines for SE Queensland	3 month ARI storm event	0.5 x Q_{1year} (flow)

2.2 Frequent and infrequent design rainfalls (IFDs)

Design rainfall estimates in the frequent to infrequent occurrence range were first made available in a consistent manner in Australia with the publication of the 1958 edition of Australian Rainfall and Run-off by the Institution of Engineers (1958). Since then these Intensity-Frequency-Duration (IFD) design rainfalls have been revised in 1977 and 1987 by the Bureau of Meteorology.

Each successive set of IFDs has utilised the available data and methods to incorporate:

- Larger rain gauge networks and longer periods of record
- New statistical techniques
- More advanced methods for interpolating between rainfall gauge sites

In addition, significant advances in computing power have allowed more advanced approaches to be adopted with each successive revision.

The methods of disseminating each successive revision of IFDs has also changed from equations, map of isohyets that needed to be read and the values plotted manually; and, more recently, software and on-line dissemination.

2.3 Rare design rainfalls

A method for deriving design rainfalls less frequent than 1% AEP was first provided in the 1987 edition of Australian Rainfall and Runoff (ARR87) (Institution of Engineers, 1987). This was a pragmatic, curve fitting procedure between the 1% and 2% AEP design rainfalls and the Probable Maximum Precipitation (PMP).

More recently, one to five day rainfall estimates in the infrequent to rare range, have been generated using a method developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH). The Cooperative Research Centre – FOcussed Rainfall Growth Estimation (CRC-FORGE) method (Nandakumar *et al*., 1997) was based on the UK Institute of Hydrology FORGE concept of using pooled rainfall data in a homogeneous region to derive growth curves at focal stations. Since its development and application to Victoria, the CRC-FORGE method has been applied to each state and some parts of the Northern Territory. The references for each of the state CRC-FORGE estimates are listed in Table 3.

Table 3. State CRC-FORGE estimates

State	Reference
New South Wales / ACT	Nandakumar *et al*, 2012
Queensland	Hargraves, 2004
South Australia	Hill *et al*, 2000
Tasmania	Gamble *et al*, 1998
Victoria	Nandakumar *et al*, 1997
Western Australia	Durrant *et al*, 2004

3. NEW DESIGN RAINFALLS

The Bureau has recently completed an eight year project to revise the design rainfalls for the categories of very frequent, frequent, infrequent and rare. That is, for probabilities from 12 EY to those with probabilities of 0.05% AEP. The project consisted of two phases:

- Phase 1 – revision of design rainfalls for probabilities of 1 EY to 1% AEP
- Phase 2 – revision of design rainfalls
  - More frequent than 1 EY
  - From 1% to 0.05%

Phase 1 of the project was completed with the new Intensity-Frequency-Duration (IFD) design rainfalls released on 1 July 2013. Phase 2 was completed in December 2015 in conjunction with ARR2015.

3.1 Frequent to infrequent design rainfalls (IFDs)

The revision of the IFDs was undertaken for a number of reasons:

- The availability of longer rainfall records (nearly 30 years more data)
- Access to expanded data sets incorporating rainfall data collected by organisations across Australia under the terms of the Water Regulations 2008
- New statistical analysis and gridding techniques
- The requirement of users for IFDs for shorter durations for use in urban studies and longer durations for use in the design of retarding basins.

Details of the data adopted for the new IFDs are summarised in Table 4 with a summary of the data used for the old ARR87 IFDs provided for comparison.

Table 4. Comparison of Data used for New IFDs and ARR87 IFDs

Step	New IFDs	ARR87 IFDs
Number of rainfall stations	Daily read – 8074 Continuous – 2280	Daily read – 7500 Continuous – 600
Period of record	All available records up to 2012	All available records up to ~1983
Length of record used in analyses	Daily read > 30 years Continuous > 8 years	Daily read > 30 years Continuous > 6 years
Source of data	Organisations collecting rainfall data	Primarily Bureau of Meteorology

In addition to a greatly expanded data base, the new IFDs used contemporary methods for the analysis of the rainfall data. The methods used to derive the ARR87 IFDs relied on subjective, manual interpolation to fill in areas with limited rainfall data. Additional computing capacity now available allowed more objective gridding techniques to be used, which provided a consistent, repeatable interpolation method across Australia. In addition, there have been developments in the statistical analysis of data since the estimation of the ARR87 IFDs, such as the use of L-moments in fitting a probability distribution to the data, which are considered to be more reliable. Table 5 provides a summary of the methods used for deriving the new IFDs and gives a comparison to those methods used in the estimation of the ARR87 IFDs.

Table 5. Comparison of Methods used for New IFDs and ARR87 IFDs

Step	New IFDs	ARR87 IFDs
Extreme value series	Annual Maximum Series (AMS)	Annual Maximum Series (AMS)
Frequency analysis	Generalised Extreme Value (GEV) distribution fitted using L-moments	Log-Pearson Type III (LPIII) distribution fitted using method of moments
Extension of sub-daily rainfall statistics to daily read stations	Bayesian Generalised Least Squares Regression (BGLSR)	Principal Component Analysis
Gridding	Regionalised at-site distribution parameters gridded using ANUSPLIN	Maps hand-drawn to at-site distribution parameters, digitised and gridded using an early version of ANUSPLIN

The data and method summarised above produced new IFDs estimates across Australia for the standard durations and standard probabilities listed in Table 6. The new IFDs are provided as rainfall depths in millimetres (mm) for the following standard durations and standard probabilities which include durations shorter than five minutes and longer than three days. In addition, the IFDs for durations shorter than one hour are provided in five minute increments rather than six minute increments as this is more keeping with the time step commonly adopted in hydrologic modelling.

Table 6. IFD Outputs

Output	Values	Units
Standard durations	1, 2, 3, 4, 5, 10, 15, 30 1, 2, 3, 6, 12 1, 2, 3, 4, 5, 6, 7	Minutes Hours Days
Standard probabilities	1 50%, 20%, 10%, 5%, 2%, 1%	EY AEP

As is to be expected, there are differences between the old and new IFDs which vary across Australia and with duration and AEP. Some of the difference is due to increased data availability in locations that previously had limited data, and some is due to the different methods for statistical analysis and interpolation used for the new IFDs. Examples of the differences between the old and the new IFDs for each capital city are provided on the new IFD webpage. More details on changes to the IFDs specifically across Tasmania can be found in Jolly *et al* (2015).

3.2 Very frequent design rainfalls

As discussed in the previous section, design rainfalls for probabilities more frequent than 1 EY (or 1 year ARI) have not previously been provided. In light of this, the provision of IFDs for probabilities more frequent than 1 EY was identified as a priority for Phase 2 of the IFD Revision Project. Producing these values will help to improve the consistency of design flow estimation for WSUD in urban development by supplying nationally consistent, scientifically based sub-annual IFDs for use with the design guidelines.

To ensure consistency between the very frequent design rainfalls and the IFDs, the overall approach adopted for the sub-annual IFDs was similar to that used for the new IFDs. However some changes will be necessary because of the increased frequency of occurrence. These changes are summarised below but are discussed in more detail in The *et al* (2015).

<u>Database</u>
The data base adopted was the quality controlled data base collated for the new IFDs. However, as very frequent design rainfall estimates are required for the more frequent probabilities of 12, 6, 4, 3, and 2 EY, additional stations with shorter record lengths were also included. The advantage of the inclusion of rainfall stations with shorter periods of records was to improve the spatial coverage of the data. The disadvantage was that the data from the additional stations have been required to be quality controlled to the same degree as the existing data base, which has been a time consuming process (Green *et al* 2011; 2012).

<u>Extreme value series</u>
For the new IFDs the Annual Maximum Series (AMS) was extracted for each station and a Generalised Extreme Value (GEV) distribution fitted using L-moments. However, the use of the AMS, directly or with a conversion factor for probabilities more frequent than 10% AEP, is not appropriate for events occurring more frequently than once a year. Therefore, for the very frequent design rainfalls it is necessary to adopt a Partial Duration Series (PDS) approach to estimate probabilities for events occurring more frequently than once a year.

<u>Distribution</u>
As part of the analyses undertaken for the new IFDs, a range of distributions were trialed using single site analysis in order to assess the most appropriate distribution to adopt across Australia for both the AMS and PDS. The distributions that were found to produce the best fit on an at-site analysis were the GEV distribution for the AMS and the Generalised Pareto (GPA) distribution for the PDS. The same results were reached using regional estimates. After further testing, the GPA distribution was fitted to the PDS for all stations which met the required record length.

<u>Regional frequency analysis</u>
Consistent with the new IFDs, regional frequency analysis was undertaken using L-moments extracted from each of the at-site frequency distributions. The L-moments were used to estimate the parameters of the selected GPA distribution.

<u>Ratios</u>
A ratio based approach was adopted to derive the very frequent design rainfall quantiles with the 50% AEP new IFDs being used as the benchmark.

<u>Gridding</u>
In order to enable very frequent design rainfalls to be derived at any point in Australia, the parameters of the selected distribution were gridded using ANUSPLIN in the same manner as was undertaken for the new IFDs (The *et al*, 2014). This will enable very frequent design rainfalls to be calculated for probabilities of 2, 3, 4, 6 and 12 EY and for the standard durations.

3.3 Rare design rainfalls

As discussed in the previous section, rare design rainfall estimates were derived by each state (and parts of the Northern Territory) using the CRCFORGE method developed by Nandakumar *et al* (1997). Although all the rare design rainfalls estimates were derived using essentially the same method, there were variations in the way each state applied the method. These differences included:

- Differences in the cut-off period for data
- Differences in record length thresholds adopted for the various steps
- Development of separate quality controlled rainfall maxima databases by each state
- The adoption of different points for the 'anchoring' of the growth curves
- Consideration of seasonality
- Differences in gridding settings and smoothing processes.

These differences were exacerbated by the fact that the application of the CRC-FORGE to each of the states was undertaken over a period of 15 years with increasing length of record and availability of more advanced techniques and resulted in inconsistencies which are particularly apparent in overlapping state border areas.

Various options for deriving new rare design estimates were considered including:

- Using the existing gridded CRC-FORGE data
- Applying the CRC-FORGE from scratch to the new IFD AMS database with some optimisation of methods including gridding / smoothing etc
- New / updated approach applied to the new IFD database.

After testing each of the approaches, it was found that the third option was the most appropriate as it adopted a new approach which was more consistent with the new IFDs and overcame the limitations of the CRC-FORGE method especially with the spatial dependence model.

The approach adopted is a regionalised LH-moments method which uses the quality controlled data base established for the new IFDs but which places more weight on the larger (rarer) rainfall events. Relationships between the LH moments and various geographic and meteorological factors (such as Mean Annual Rainfall) were derived and rare design rainfall quantiles produced for homogenous regions around Australia.

To ensure consistency between the new rare design rainfalls and the new IFDs, the rare design rainfalls were 'anchored' to the new IFD for the 1% AEP. Further details on the estimation of new rare design rainfalls can be found in Green *et al* (2015).

4. DISSEMINATION

The new design rainfalls are available from the Bureau's website at http://www.bom.gov.au/water/designRainfalls/ifd/index.shtml. The new design rainfalls are provided both as a table – which can be downloaded as a .csv file – and as a chart – which can be downloaded as a .jpg file. The webpage also contains more detailed information on how the new IFDs were derived; how the new IFDs should be used; provides maps comparing the new IFDs to the old IFDs; and a series of FAQs.

In addition, the new long duration Areal Reduction Factors to be used with the new design rainfalls are provided; advice on incorporating climate into the new IFDs; advice on deriving seasonal design rainfalls; and information on estimating the uncertainty associated with the new IFDs. This provides a free 'one stop shop' for design rainfalls for any location in Australia.

5. CONCLUSIONS

The Bureau of Meteorology has recently completed an eight year project to provide new design rainfall estimates for probabilities from 12 EY to 0.05% AEP which covers the categories of very frequent;

frequent and infrequent; and rare design rainfalls. These design rainfall estimated are based on a comprehensive rainfall data base comprising data collected by the Bureau and organisations around Australia which have been analysed using the latest methods. They provide a clear, consistent point of reference for all hydraulic and hydrologic analysis in Australia.

6. REFERENCES

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