The Revised Intensity-Frequency-Duration (IFD) Design Rainfall Estimates for Australia – An Overview

Janice Green
IFD Revision Project Manager, Climate and Water Division, Bureau of Meteorology, Canberra, Australia

Karin Xuereb
Senior Meteorologist, Climate and Water Division, Bureau of Meteorology, Melbourne, Australia

Fiona Johnson
Hydrologist, Climate and Water Division, Bureau of Meteorology, Sydney, Australia

Garry Moore
Technical Officer, Climate and Water Division, Bureau of Meteorology, Melbourne, Australia

Cynthia The
Hydrologist, Climate and Water Division, Bureau of Meteorology, Sydney, Australia

The Bureau of Meteorology has recently finalised a revision of the Intensity-Frequency-Duration (IFD) design rainfall estimates, with the revised point IFDs due to be released in November 2012. The revision used a greatly expanded rainfall database in addition to adopting more statistically rigorous methods that are most appropriate to Australian rainfall data. The revised IFD estimates better meet the changing needs of users by providing estimates for the shorter durations and more frequent Annual Exceedance Probabilities (AEPs) that are required for urban design. The revised IFDs are being disseminated via a new webpage which provides the information in a format that is better suited to the currents needs of practitioners undertaking design flood studies.

1. INTRODUCTION

Design rainfall estimates are an essential component of the design of infrastructure including gutters, roofs, culverts, stormwater drains, flood mitigation levees and retarding basins. The previous Intensity-Frequency-Duration (IFD) estimates for Australia were developed by the Bureau of Meteorology (the Bureau) over 20 years ago using a database comprised primarily of information from the Bureau's network of daily read and continuous rainfall stations and adopting techniques for the statistical analysis of the data that were considered appropriate at the time. The IFDs were disseminated as hard copy maps in Volume 2 of Australian Rainfall and Runoff (AR&R87) (IEAust, 1987) and either a graphical or an analytical process was required to derive IFDs for a specific site. The focus of the IFDs was the design of structures on relatively large rural catchments and therefore durations of less than five minutes were not considered necessary. The approach adopted for the IFD estimates contained in AR&R87 is summarised in Table 1.

In the intervening years, the Bureau's network of rainfall stations has been expanded and more than 20 years of additional data have been collected resulting in an increase in the number of stations with sufficient length of record to be included in the analyses. In addition, the Bureau now has ready access, under terms of the Water Regulations 2008, to daily-read and continuous rainfall data collected by other organisations which supplements the Bureau's network particularly in urban areas and areas of steep rainfall gradients. In parallel with the expansion of the rainfall database, there have been significant advances in statistical methods, gridding procedures, and information dissemination techniques which make a revision of the IFD estimates long overdue. Further, the requirements of the end-users have changed with a significant greatly focus on urban design on small catchments than with the AR&RR87 IFDs, necessitating the provision of IFD estimates for durations as short as one minute. This has required an emphasis on providing sub-hourly IFDs and the need to develop methods that optimise the information available from the continuous rainfall stations.

Table 1 Summary of AR&R87 IFD method

Variable	Output
Data	Primarily Bureau stations
Record length	up to 1983; 7500 daily read > 30 years; 600 pluviographs > 6 years
Durations	5 minutes to 72 hours (3 days)
Average Recurrence Intervals (ARIs)	1 year to 100 years
Frequency analysis	Annual maximum series; method of moments; Log-Pearson Type III
Seasonal estimates	No
Mapping	Manual drawing of the isohyets
Confidence Intervals	No
Climate Change	No; stationary climate assumed; climatic trends assumed to have negligible effect on IFDs
Delivery method	Maps; IFD tables & charts calculated on-line

In the following sections an overview of the work that has been undertaken by the Bureau of Meteorology into revising the IFD estimates will be presented.

2. DATABASE

2.1. Sources of data

The previous IFD estimates were based primarily on the Bureau's network of daily read and continuous rainfall stations which consisted of approximately 7500 daily read rainfall stations with greater than 30 years of data and 600 continuous rainfall stations with greater than 6 years of data.

In the intervening years, the Bureau's network of rainfall stations has been expanded and more than 20 years of additional data have been collected resulting in an increase in the number of stations with sufficient length of record to be included in the analyses. In 2011, the Bureau of Meteorology's Australian Data Archive for Meteorology (ADAM) contained:

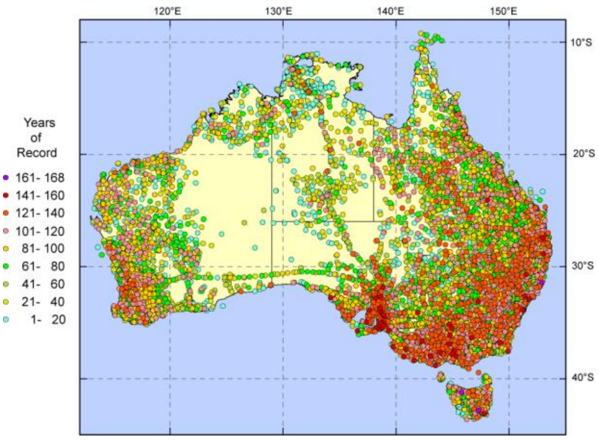
- approximately 20 000 daily read rainfall stations (both open and closed) starting in 1800
- nearly 1500 continuous rainfall stations – using both Dines tilting syphon pluviograph (DINES) and Tipping Bucket Rain Gauge (TBRG) instrumentation.

In addition, the Bureau now has ready access, under terms of the Water Regulations 2008, to daily-read and continuous rainfall data collected by other organisations. These additional stations supplement the Bureau's network particularly in areas of steep rainfall gradients and urban areas. Data from the following additional rainfall stations have been received via the Water Regulations:

- approximately 350 daily read rainfall stations
- approximately 2175 continuous rainfall stations.

The effect of more than doubling the number of continuous rainfall stations upon which the IFD estimates are derived is a significant improvement in the accuracy and representativeness of the IFD estimates, especially for sub-daily durations and in urban areas.

The location of the rainfall stations used in revising the IFDs and the period of record are shown in Figure 1(a) for the daily read stations and Figure 1(b) for the continuous rainfall stations.



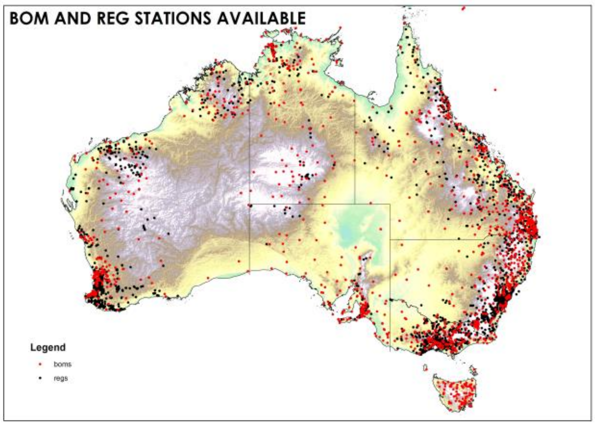


Figure 1(a) Daily read rainfall stations **Figure 1(b) Continuous rainfall stations**

2.2. Quality controlling of data

For the previous IFDs, limited manual checking of the values of the Annual Maximum Series (AMS) was undertaken. For the revised IFDs a detailed and systematic approach for quality controlling all the daily read data and the Partial Duration Series (PDS) of the continuous rainfall was applied. Automated quality controlling software was developed to assist in the identification and correction of a significant number of errors. The automated procedures were supplemented by the manual checking of the residual suspect data using the functionalities of the Bureau's Quality Monitoring System (QMS). Further details on the quality controlling of the rainfall data can be found in Green et al (2012).

In addition to being used in the revision of the IFDs, it is proposed that the quality controlled database of rainfall data be made available to practitioners for use in design flood studies.

3. AT-SITE FREQUENCY ANALYSIS

As shown in Table 1, the previous IFD estimates were derived using statistical techniques that were considered appropriate at the time. A Log-Pearson Type III distribution was fitted to the annual maximum series of rainfall data using the method of moments.

However, in recent years analyses have been undertaken as part of the development and application of the Co-operative Research Centre for Catchment Hydrology Focussed Regional Growth Estimation (CRC-FORGE) approach for the estimation of design rainfalls for Annual Exceedance Probabilities (AEPs) from 1% to 0.05% (Nandakumar et al, 1997). These analyses found that a Generalised Extreme Variable (GEV) distribution fitted using L-moments (Hosking and Wallis, 1997) was the most appropriate approach for Australian rainfall data.

In order to assess the most appropriate distribution to adopt across Australia for both the AMS and the PDS for the IFD revision project, a range of distributions were trialed using single site analysis. Five distributions – GEV, Generalised Logistic (GLO), Generalised Normal (GNO), Pearson Type III (PE3) and Generalised Pareto (GPA) – were fitted to both the AMS and PDS extracted from the available long-terms continuous rainfall stations for durations of 6, 12, 18, and 30 minutes and 1, 2, 3, 6, and 12 hours. The goodness of fit of each distribution was assessed using the approach recommended by Hosking and Wallis (1997) which uses a goodness of fit measure Z^{Dist} with a threshold $|Z^{Dist}| \leq 1.64$. The following distributions found to produce to produce the best fit on an at-site analysis:

- Annual Maximum Series – Generalised Extreme Value (GEV)
- Partial Duration Series – Generalised Pareto (GPA)

The comparison of distributions was subsequently repeated for regional estimates with the same results.

On the basis of the results of the above comparison, the GEV distribution was fitted to the previously extracted AMS and the GPA was fitted to the PDS for all stations which met the record length criteria of thirty years for daily read rainfall stations and nine years for continuous rainfall stations.

4. REGIONAL FREQUENCY ANALYSIS

Regional frequency analysis was undertaken using the L-moments which were extracted from each of the frequency distributions. While for durations of 1 day and longer this was a fairly straightforward approach, for sub-daily durations the scarcity of long term continuous rainfall records meant that an alternative approach was needed to supplement the available data. For the IFD revision project, a Bayesian Generalised Least Squares Regression (BGLSR) approach was adopted.

4.1. Daily durations (24 hours to 168 hours)

The linear combinations of the data (L-moments) (Hosking and Wallis, 1997) of mean, variation (L-CV) and skewness (L-skewness) were used to summarise the statistical properties of the extreme value series data at each station location. L-moments are commonly used in rainfall and flood frequency analysis (Hosking and Wallis, 1997) due to their efficiency in fitting the data and lack of bias in the sample estimates, particularly in the higher order moments, when compared to ordinary moments.

4.2. Sub-daily durations (1 hour to 12 hours)

At sites at which there was a continuous rainfall station with more than eight years of record, the mean, L-CV and L-skewness, were determined from the at-site extreme value series for each duration.

The continuous rainfall stations were also used to derive prediction equations between site characteristics and the sub-daily L-moments. This was done in order to be able to estimate sub-daily rainfall parameters based on site characteristics and daily rainfall statistics to improve the spatial coverage of sub-daily data.

As can be seen from Figures 1(a) and 1(b) the spatial coverage of sub-daily rainfall stations is considerably less than that of the daily read stations. Therefore, a method is needed to improve the spatial coverage of the sub-daily data. This is most commonly done using information from the daily read stations with statistics of sub-daily data being inferred from those of the daily data. For the previous IFDs, Principal Component Analysis (PCA) followed by regression was used to derive equations for predicting the ARIs at durations below 24 hours from the ARI for the 24, 48 and 72-hour durations. However, a major weakness of the previously adopted approaches is their inability to account for variation in record lengths from site to site and inter-station correlation

The approach that was adopted for the revised IFDs was Bayesian Generalised Least Squares Regression (BGLSR) because it accounts for possible cross-validation and unequal variance between stations by constructing an error covariance matrix and can explicitly account for sampling uncertainty and intersite dependence. A further advantage of the BGLSR is that the Bayesian formulation allows for the separation of sampling and statistical modeling errors. This is important because it was found that the sampling errors dominate the total error in the statistical model. The BGLSR produces estimates of the standard error in:

- the regression coefficient
- the predicted values at-site used in establishing the regression equations

- the predicted values at daily rainfall stations (i.e. ungauged sites not used in deriving the regression)

The error variances for the predictions are comprised of the regional model error and the sampling variance. Further details on the Bayesian GLSR approach can be found in Reis et al (2005) and Madsen et al (2002, 2005).

Following a detailed assessment of the influence various factors have large rainfalls, the following values (predictors) were used to predict the mean, L-CV and L-skewness (predicants) using in the BGLSR:

- Location (latitude and longitude)
- Elevation
- Slope
- Aspect
- Distance from the coast
- Mean annual rainfall
- Rainfall statistics for 24 hour, 48 hour and 72 hour durations - mean, L-CV and L-skewness.

The regression equations derived from the BGLSR were then applied to the daily read stations to predict the sub-daily L-moments at the daily station locations. This allowed for a greater density of sub-daily data to be used in gridding across Australia which is described below.

5. REGIONALISATION

Regionalisation recognises that for stations with short records, there is considerable uncertainty when estimating the parameters of probability distributions and short records can bias estimates of rainfall statistics. To overcome this, it is assumed that information can be combined from multiple stations to give more accurate estimates of the parameters of the extreme value probability distributions.

For the revision of the IFDs, regionalisation has been used to estimate the L-CV and L-Skewness with more confidence. The regionalisation approach adopted is generally called the “index flood procedure” (Hosking and Wallis, 1997). This approach assumes that sites can be grouped into homogenous regions, such that all sites in the region have the same probability distribution, other than a scaling factor. The scaling factor is then normally termed the index flood or in this case, since the regionalisation is of rainfall data, the “index rainfall”. The index rainfall is the mean (i.e. first L-moment) of the extreme value series data at the station location.

For the IFD revision project, the station point estimates were regionalised using a Region of Influence Approach (ROI). The ROI approach assumes that all the stations in the region of the station of interest have a common probability distribution which only needs to be scaled by a site specific factor. The assumptions of the approach are, firstly, that the specified probability distribution (GEV in the case of the AMS) is appropriate; that the region is truly homogenous; and, finally, that sites are independent or that their dependence is quantified. After trialling various approaches homogenous ROIs were defined as circle which was expanded from the site of interest until it included sufficient rainfall stations to provide 500 station years of record.

6. GRIDDING OF GEV PARAMETERS

The regionalisation process resulted in estimates of the GEV parameters at all station locations, which were combined with the mean of the extreme value series at that site to estimate rainfall quantiles for any required exceedance probability. However IFD estimates are required across Australia, not just at station locations and therefore the results of the analyses needed to be extended in some way to ungauged locations. For the previous IFDs, the gridding of the regionalised rainfall intensities was undertaken manually. Although a splining program was used its purpose was only to translate the hand-drawn contours into grid format.

For the revised IFDs, the software package ANUSPLIN (Hutchinson 2007) was chosen to grid the GEV parameters so that IFD estimates are available for any point in Australia. ANUSPLIN applies thin plate smoothing splines to interpolate and smooth multi-variate data. The degree of smoothing of the fitted functions was determined through generalised cross validation. The splines are fitted using three independent variables; latitude, longitude and elevation. The elevation scale was exaggerated by a factor of 100 to represent the importance that elevation has on precipitation patterns (Hutchinson 1995).

The GEV parameters have been being gridded in ANUSPLIN rather than the rainfall depths, as earlier testing has shown little difference in the resulting quantile estimates if the point parameter or point rainfall depths are gridded. Gridding the GEV parameters gives more flexibility in the choice of exceedance probabilities that can be extracted and enable the provision of a greater number of AEPs.

7. CALCULATION OF GROWTH FACTORS AND RAINFALL DEPTHS

The outputs of the ANUSPLIN analysis were grids across Australia for each duration of index rainfall and the GEV shape (alpha) and scale (kappa) parameters. These were then processed to firstly estimate the growth factors for each grid location and then the rainfall depths for each exceedance probability.

Due to the different values selected for analysis in the AMS and the PDS, fitted distributions for the two series will lead to different estimates of the rainfall quantiles. For frequent events, the PDS is considered to be more reliable as it will include many rainfall events around the exceedance probability of interest. A conversion factor therefore needed to be applied to the AMS rainfall estimates for events more frequent than the 10% AEP to account for the lower estimates than those obtained if the PDS had been used. The adopted conversion factors were 1.11 for the 50% AEP and 1.02 for the 20% AEP. These conversion factors were based on the ratio of the 50% and 20% AEP estimates of the 24 hour rainfall depth from the AMS and PDS respectively, averaged across Australia.

8. OUTPUTS

The outputs from the revision of the IFD estimates reflect the change in the needs of the end-users for IFD information and the technology available for dissemination of the information.

8.1. Durations

The extent of durations considered in the previous IFD relationships (outlined in Table 1), was 5 minutes to 72 hours. In response to changes in user requirements, the revised IFD estimates will be provided for durations from 1 minute to 168 hours (7 days). In addition advice on how to extrapolate to durations of less than one minute and greater than 7 days will also provided. The broader range of duration reflects the changed requirements of end-users with the increased focus on very short durations for urban designs such as gutters and the longer durations for retarding basins.

8.2. AEPs

AR&R87 provided advice on how to apply the algebraic method the derive IFDs for AEPs of 0.5 and 0.2%. Book VI of the 1999 edition of AR&R (Nathan & Weinmann, 1999) provided details on how to interpolate between the 1% AEP and the Probable Maximum Precipitation (PMP) for the cases where rare regional estimates were available and where they weren't. Rare regional estimates (CRCFORGE estimates) have now been derived by each state for AEPs from 1% to 0.05%, however, there are minor differences in the way in which they have been derived and how they are applied.

The revised IFD information will be provided for AEPs to 1%. In addition, the revised IFD information will be blended with the CRCFORGE estimates for each state to enable a smooth rainfall frequency curve to be derived to an AEP of 0.05% using an approach that is consistent across Australia.

8.3. Dissemination

The series of six master maps contained in Volume 2 of AR&R87 represented a significant advancement in the dissemination of IFD information at the time. However, with the capability to provide this information on-line, for example, via the Bureau's Computerised Design IFD Rainfall System (CDIRS), the hard copy maps are used less frequently by practitioners. Although CDIRS made the estimation of IFDs considerably quicker and more consistent, some limitations included the inability to provide IFD estimates for non-standard durations and AEPs (including AEPs less than 1%) and the limitation of IFDs only being able to be estimated for a single point at a time.

The revised point IFD estimates will be disseminated in an electronic format via a new webpage which can be accessed from the Bureau's website. The new interface will allow users to select the AEPs and durations for which IFDs are required; allow IFDs for multiple locations to be derived at the one time; provide the IFDs as both depths and intensities, and facilitate the downloading of the revised IFD tables in either text or csv format and the revised IFD curves as jpegs.

8.4. Enhancements

Over the next six months, work will continue on the development of enhancements to the revised point IFDs. These enhancements will include areal IFDs, seasonal IFDs, and uncertainty estimates. As they become available, these enhancements will be incorporated into the new IFD website.

8.5. Implications of the revised IFDs

A detailed comparison on a national and regional basis between the revised IFDs and the AR&R87 IFDs is currently being undertaken; although, at the time of writing the results of these comparisons were not available. However, information on the differences between the revised IFDs and the AR&R87 IFDs will be provided on the new web-page at the same time as the revised points IFDs are released. This information will be provided both as maps and as tables of percentage changes.

8.6. Climate change advice

The revised IFDs are for the current climatic regime. As part of the overall AR&R revision a climate change research strategy paper has been prepared to enhance understanding of how projected climate change may alter the behaviour of factors that influence the estimation of the design floods that are used in policy decisions involving infrastructure, town planning, floodplain management and flood warning and emergency management.

The AR&R Revision Climate Change Research Strategy identifies priorities for research direction to be undertaken over both the short term (Stage 1 – one year) and the longer term (Stage 2 – four years). The Strategy identifies five research themes:

1. Rainfall intensity-frequency-duration relationships
2. Rainfall temporal patterns
3. Continuous rainfall sequences
4. Antecedent conditions (including baseflow)
5. Simultaneous extremes

At the time of writing, funding has been provided for Stage 1 of Themes 1 and 2. In the interim, advice will be provided on how to consider the impact of climate change in projects that use design rainfalls and have life spans of long enough duration such that climate change may affect the project.

9. CONCLUSIONS

The Bureau of Meteorology has revised the IFD estimates that are used by practitioners for the design of infrastructure ranging from gutters to dams; the revised point IFDs will be released in November 2012. Over the subsequent six months enhancements to the point IFDs will be rolled out.

The revision used a greatly expanded rainfall database incorporating not only the more than 20 years of additional data collected at the Bureau's gauges but also data from the rain gauge networks operated by other organizations. All the data were subject to rigorous quality controlling procedures.

In addition, the revision adopted more statistically rigorous techniques such as the Generalised Extreme Variable distribution and L-moment for rainfall frequency analysis, Bayesian Generalised Least Squares Regression for deriving sub-daily rainfall statistics, GIS based methods for gridding and an "index rainfall procedure" for regionalisation.

The revised IFD estimates have been provided for durations from 1 minute to 7 days. The AEPs for which the revised IFDs have been provided are from 50% to 1%. The revised IFD information has been blended with the existing CRCFORGE estimates for each state for AEPs from 1% to 0.05% to provide to enable a smooth rainfall frequency curve to be derived to an AEP of 0.05%. The dissemination of the revised IFD estimates has been undertaken in electronic format via a web interface which enables users to derive both point and areal IFDs.

10. REFERENCES

Green, J.H., Johnson, J., McKay, D., Podger, P., Sugiyanto, M., and Siriwardena, L. (2012). "Quality Controlling Daily Read Rainfall Data for the Intensity-Frequency Duration (IFD) Revision Rainfall Project". Accepted for presentation at Hydrology and Water Resources Symposium, Sydney, NSW, November 2012.

Hosking, J.R.M. and Wallis, J.R., (1997). Regional Frequency Analysis: An Approach Based on L-Moments. Cambridge University Press, Cambridge, UK. 224 pp.

Hutchinson, M.F. (1995), Interpolating mean rainfall using thin plate smoothing splines, Int J Geographical Information Systems, 9(4), 385-403

Hutchinson, M. F. (2007), ANUSPLIN version 4.37 User Guide, The Australian National University, Centre for Resources and Environmental Studies, Canberra

Institution of Engineers, Australia (1987) (AR&R87). Australian Rainfall & Runoff - A Guide to Flood Estimation Volumes 1 and 2. Institution of Engineers, Australia, Barton, ACT.

Madsen, H., Mikkelsen, P.S., Rosbjerg, D. and Harremoes, P. (2002), Regional estimation of rainfall intensity duration curves using generalised least squares regression of partial duration series statistics. Water Resources Research, 38 (11), 1239

Madsen, H., Arnbjerg-Neilsen, K. and Mikkelsen, P.S. (2009), Update of regional intensity-duration-frequency curves in Denmark: Tendency towards increased storm intensities. Atmospheric Research, 92, 343-349

Nandakumar, N., Weinmann, P. E., Mein, R. G., Nathan, R. J. (1997), Estimation of Extreme Rainfalls for Victoria using the CRCFORGE Method, CRC for Catchment Hydrology.

Nathan, RJ and Weinmann, E, (1999) Estimation of Large to Extreme Floods, Book VI in Australian Rainfall and Runoff - A Guide to Flood Estimation , The Institution of Engineers, Australia, Barton, ACT, 1999.

Reis Jr., D.S., Stedinger, J.R. and Martins, E.S. (2005), Bayesian GLS regression with application to LP3 regional skew estimation. Water Resour Res. 41, W10419, (1) 1029.